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GAIT CYCLE OF SLOW WALKING IN HIGH HEELS

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Authors' contribution
A. Study design/planning
B. Data collection/entry
C. Data analysis/statistics
D. Data interpretation
E. Preparation of manuscript
F. Literature analysis/search
G. Funds collection

Summary

Background. The aim of the work was to ascertain the differences in the temporal characteristics of the gait cycle of slow walking in high heels. The study particularly focused on a group of women who started to wear high heels more often.

Material and methods. The Pedar X System (Novel, Germany) was used to analyze the temporal characteristics of the gait cycle. Average values of temporal variables in both feet were ascertained based on the measured functions of maximal peak pressure (PPmax) and maximal vertical force (MVFmax) depending on time.

Results. Slow walking in high heels, as compared to slow walking in flat shoes, resulted in shortening the gait cycle in all its phases. This in turn increased the frequency of steps in high heels. While walking at a speed of v1=0.97 m.s-1 (slow speed) and v2=0.56 m.s-1 (very slow speed), there were no differences in stance/swing ratio between high heels and flat shoes.

Conclusions. Slow walking speeds can be considered to be suitable for women who have recently started walking in high-heeled shoes and have had no previous experience with them.

Keywords: walking speed, stride, swing, shoes, pressure

Introduction

High heels vs. flat shoes

For most women, walking in high heel shoes (HH) for long periods of time usually begins when they start working in a professional and/or office environment. Until then, women rarely wear HH except for formal social events. A standard shoe typically features a heel elevated up to 2 cm, whereas high-heeled shoes are characterized by heels that are taller than the shoe's front part, with the elevation often exceeding 10 cm [1]. When walking in low heels, the center of mass (COM) falls at an even higher level than when walking barefoot. The rear additional arc of the hip joint movement is therefore even flatter. During the foot transfer phase through the vertical, the ankle is almost the same height, as it is only in this gait phase that the foot enters plantar flexion on the surface. Conversely, when wearing HH, the ankle is in plantar flexion, and the COM is shifted forward, necessitating greater postural control [2].

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Gait in high-heel shoes

The distribution of overall load on the foot while standing changes in relation to internal factors: the shape of the arch of the foot, the direction of the body axis opposite to the direction of gravitation – the center of pressure (COP) into the support surface, the position of the femoral head in the hip joint, and the position and configuration of the axial skeleton [3,4]. The distribution also depends on external factors: inclination of the support surface, its profile, and friction properties of surface and shoes. The forces of the foot and ground reaction forces are distributed on a larger area during the contact of the foot with the ground. The COP while wearing shoes progresses from heel to toes. Barefoot, however, it is transferred along the outer edge of the foot to the fifth toe and through the metatarsal heads towards the first toe. A bare foot is partially attached to the ground in this phase and thus helps balance the body. Feet in shoes are not in direct contact with the ground, and the toes are often extended, both of which can lower the overall stability of the body [3-5].

Walking velocity in high-heel shoes

Many studies examine the impact of change in position on balance. The resulting data point to reactive chain effects from lower limbs towards the spine [1]. HH contribute to slower walking and shorter steps, but cadence is unchanged [6-8]. The average walking speed in HH is 1.23 $m.s^{-1}$ to 1.44 $m.s^{-1}$ [9]. In general, a slow walking speed is considered to be 1.12 $m.s^{-1}$, and in studies focusing on walking in HH, walking speeds of 1.3-1.4 $m.s^{-1}$ were used most often [6,10,11]. Increasing the height of the heel increases the friction of the back of the shoe against the ground, which also increases energy expenditure [12-15]. The gait cycle in HH is greatly influenced by the wearer's experience in wearing them. In a previous study, the stability of normal (regular wear, at least 3 days a week, 6 hours a day) and inexperienced (maximum twice a month) HH wearers was compared [16]. Experienced wearers had better stability during single support and faster weight transfer during double support [17-19].

According to our knowledge, the effect of HH on the gait cycle was investigated most frequently at preferred speed [9].

Entering a new professional environment often necessitates learning new skills, including adopting new behaviors. For women required to wear formal footwear, such as high-heeled shoes, adjusting to a changed gait cycle can be stressful. To mitigate this stress, proficiency in walking in high heels is essential, and the proportionality of each phase of the gait cycle should closely resemble that of walking in flat shoes.

Aim of the work

The aim of the study was to determine changes in the time characteristics of the gait cycle in non-experienced HH wearers at walking speed: $v<1$ $m.s^{-1}$. It was assumed that very slow walking in HH would cause a higher percentage duration of STANCE, and that SWING would be relatively shorter than walking in FS.

Material and methods

The study comprised 30 healthy female participants, inexperienced in walking in HH, with an average age of 21.8±2.09 years, height of 1.66±0.03 meters, weight of 55.7±4.05 kilograms, Body Mass Index (BMI) of 20.34±1.41, and shoe sizes ranging from EU 36 to 38. The exclusion criteria encompassed any musculoskeletal injury within the past year, and any current musculoskeletal pain or injury that could restrict their range of motion in the body and limbs.

Data were collected for each subject during a single session. At the beginning of each trial, the system for measuring in-shoe pressure was calibrated when standing on one leg separately for each shoe in accordance with the manufacturer's recommendations (Pedar-X). Subjects had the possibility of walking on a treadmill in both types of shoes for 3 minutes before the test started. Data were collected during 30 seconds while the subjects walked on the treadmill at the pre-set walking speeds of v_1=0.97 m.s^{-1} and v_2=0.56 m.s^{-1}. Walking speeds were chosen based on a pilot study to determine which treadmill walking speed was most comfortable and safest for research participants. The monitored values were first measured while walking in flat shoes without heels (FS), and afterwards in high heel shoes with a heel of 7 cm (HH). The comparative experiment aimed to discover the correlations among variables recorded (STANCE, SWING, STRIDE and the frequency of steps) when walking in two types of shoes (HH and FS – Figure 1), at walking speeds of v_1 and v_2.

Figure 1. The high heel shoes and flat shoes used in the study

Measuring pads with 99 sensors (Pedar-X, Novel, Germany) were used to analyze the pressure distribution under the feet in contact with the ground (Figure 2). The recording frequency was 50 Hz.

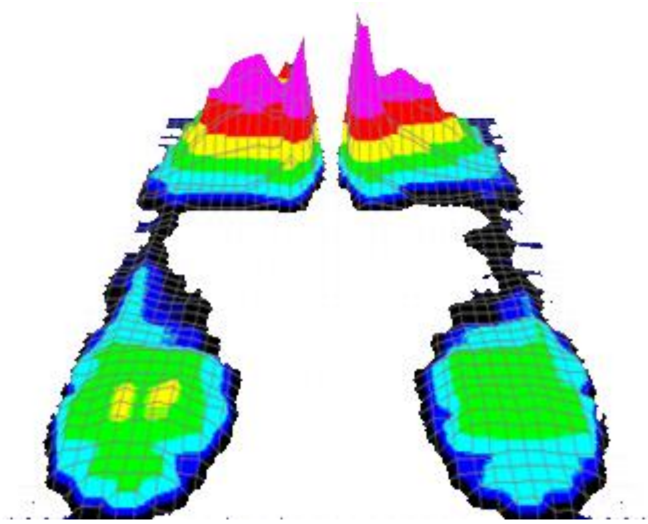

Figure 2. An example of plantar pressure distribution while walking

Temporal variables from each step (STANCE – [s]), swing phase (SWING – [s]), duration of the stride (STRIDE – [s]) and frequency of the steps per minute (FRE – [step/min]) were processed by software (Novel, Germany) based on the values of maximal peak pressure (PP_{max}) and maximal vertical force (MVF_{max}) (Figure 3).

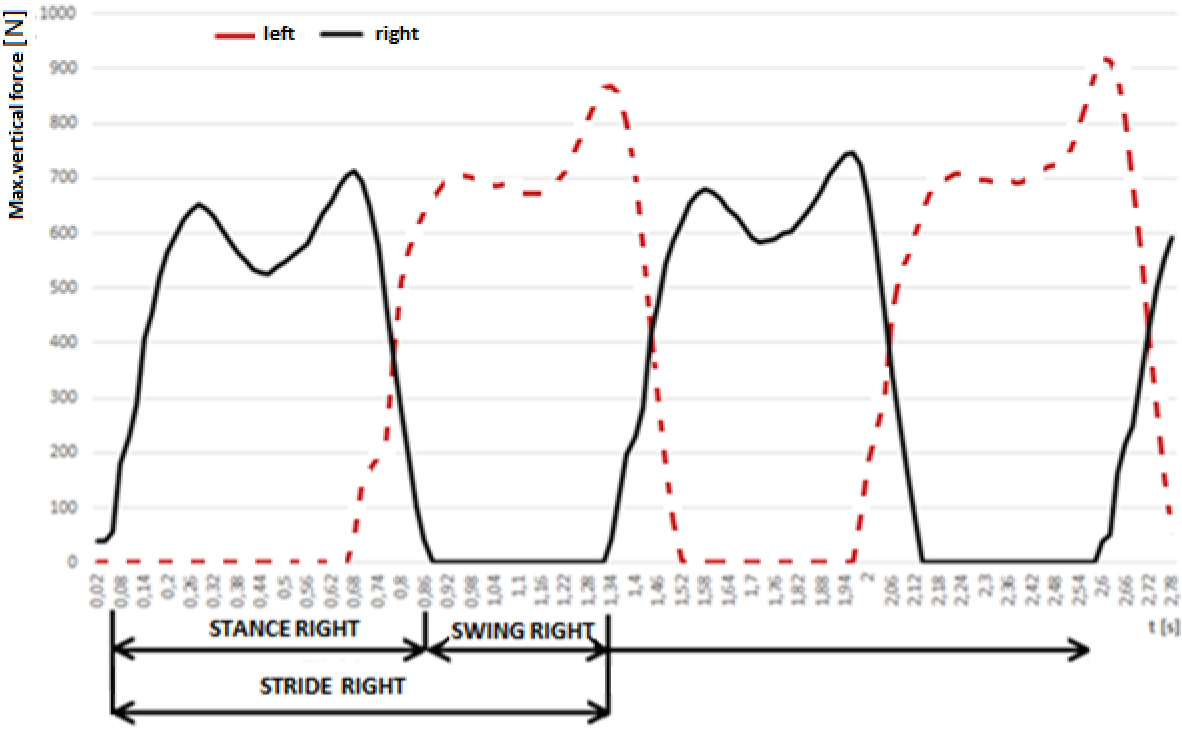

Figure 3. An example of the maximal vertical force component during gait cycle

For analyzing the relationship within time-based data, the Pearson correlation coefficient r was utilized. A paired t-test was employed to evaluate the impact of HH on the temporal aspects of the gait cycle, comparing it across HH and FS conditions in v_1, v_2. Statistical significance is determined when the t value surpasses the critical threshold of 1.669. Significance is acknowledged for measured values at ($p \leq 0.05$). To gauge the effect's size, Cohen's d was used, indicating a small effect for values between 0.2 and 0.4, a medium effect for values from 0.5 to 0.7, and a larger effect for values exceeding 0.7.

Results

The reliability of the measurement was confirmed by the correlation coefficient r. The values of r meant a moderate to strong degree of dependence of the temporal parameters of the gait cycle between HH and FS in both v_1 and v_2 (Table 1).

Table 1. Dependencies of temporal parameters of gait cycle between HH and FS

HH vs FS	STANCE[s]	SWING[s]	STRIDE[s]	FRE[steps/min.]
v_1 **r**	0.658*	0.789*	0.580*	0.789*
v_2 **r**	0.340	0.588*	0.531*	0.498*

Notes: * – significant correlation at $p<0.01$; r – correlation coefficient; v_1 – 0.97 ms^{-1}; v_2 – 0.56 ms^{-1}.

In nearly all temporal variables, significant statistical differences were observed in slow walking between HH and FS. The duration of STANCE, SWING and STRIDE in HH is significantly shorter than the duration in FS in both limbs. The average values of these variables (Table 2) for the individual gait phases of all participants show that STANCE, SWING and STRIDE duration in HH is shorter than in FS while walking at both speeds v_1 and v_2. Statistically significant results showed a higher and large effect (d>0.7). In both shoe types, the average duration's percentage ratio for each gait phase (STANCE, SWING) was comparable. At v_1, there was a 64% STANCE and 36% SWING ratio in HH, with FS showing a nearly identical ratio. For v_2, in both shoe types, the STANCE phase extended to 66%, while the SWING phase decreased to 34%. Walking in HH shoes resulted in the shortening of the gait cycle, which in turn increased the frequency of steps per minute. The average FRE in HH was 99, and in FS 92 steps per minute.

Table 2. Variations in the gait cycle phases during slow walking in HH and FS

Evaluated parameters and significance values	STANCE[s]	SWING[s]	STRIDE[s]	FRE[steps/min.]
HH (v_1)				
Aver.	0.780	0.438	1.217	99.004
SD	0.058	0.040	0.084	6.597
Ratio	64 %	36%	100%	-
FS (v_1)				
Aver.	0.828	0.476	1.304	92.468
SD	0.077	0.046	0.115	8.392
Ratio	64%	36%	100%	-
HH vs FS (v_1)				
t	-4.643	-5.241	-6.473	6.828
p	**0.000**	**0.000**	**0.000**	**0.000**
d	**0.70**	**0.87**	**0.85**	**0.85**
HH (v_2)				
Aver.	1.124	0.580	1.700	70.878
SD	0.121	0.064	0.154	7.352
Ratio	66%	34%	100%	-
FS (v_2)				
Aver.	1.215	0.613	1.829	66.303
SD	0.115	0.082	0.179	6.547
Ratio	66%	34%	100%	-
HH vs FS (v_2)				
t	-3.611	-2.430	-4.529	3.521
p	**0.001**	0.021	**0.000**	**0.001**
d	**0.76**	**0.43**	**0.76**	**0.65**

Notes: HH – high heels; FS – flat shoes; v_1 – 0.97 ms^{-1}; v_2 – 0.56 ms^{-1}; Aver. – average; SD – standard deviation; Var. – variance; Ratio – percentage phase ratio of the gait cycle; t – t values; *p* – *p*-values; d – effect size.

Statistical analysis of differences in individual gait phases and frequency of steps per minute between HH and FS confirmed statistically significant differences in all observed gait phases and step frequency at v_1 at $p<0.05$. For v_2, statistically significant variations were also verified in gait phases and step frequency, except for the SWING phase.

To provide a comprehensive overview of the results, a comparison of the individual phases of the step cycle at different walking speeds within the same shoe (HH v_1 vs HH v_2 and FS v_1 vs FS v_2) has been included (Table 3). Statistical analysis of the differences in the individual phases of walking and the frequency of steps per minute between v_1 and v_2 in HH and FS confirmed statistically significant distinctions, thereby affirming the impact of walking speed on the step cycle itself.

Table 3. Comparison of gait cycle phases at different speeds

Significance values	STANCE[s]	SWING[s]	STRIDE[s]	FRE[steps/min.]
HH (v_1) vs HH (v_2)				
t	5.795	-6.965	-7.304	2.652
p	**0.000**	**0.000**	**0.000**	**0.005**
d	**0.80**	**0.70**	**0.000**	**0.76**
FS (v_1) vs FS (v_2)				
t	6.9305	-6.532	-4.926	2.845
p	**0.000**	**0.000**	**0.000**	**0.003**
d	**0.68**	0.65	**0.76**	**0.70**

Notes: HH – high heels; FS – flat shoes; v_1 – 0.97 ms^{-1}; v_2 – 0.56 ms^{-1}; t – t values; *p* – *p*-values; d – effect size.

Discussion

Key features of walking encompass the duration of the gait cycle, rhythm, double-step length, and velocity [20]. From the perspective of clinical examination and ergometry these parameters are the easiest form of walking assessment. A change in walking parameters can occur with any handicap. In this study, it was confirmed that the inexperience of wearing HH can also be considered a handicap that affects gait naturalness. A change in walking parameters can also be influenced by age, sex, the reactive force of surface or resistance of environment [21]. This study compared individual gait phases (STANCE, STRIDE, SWING) at a slow speed of walking (v_1=0.97 $m.s^{-1}$; v_2=0.56 $m.s^{-1}$) in HH and FS, and found statistically significant differences between HH and FS. Individual gait phases were shorter while walking in HH, which also influenced the frequency of steps.

The exact duration of SWING and STANCE depends on the walking speed. At the usual walking speed of 80 m/min. STANCE represents 62% and SWING 38% [2]. It was confirmed that with decreasing walking speed, the ratio of these phases changes in terms of shortening SWING and lengthening STANCE. It was assumed that the percentage ratio of the STANCE will be higher in HH than in FS. The identical percentage ratio of SWING and STANCE while walking in HH and FS was an interesting and positive research finding. This is explained by very slow walking when women are not exposed to space-time stress, as is the case with faster walking.

Increasing heel height increases the vertical shift of the COM [13,15] which results in a change of duration of step phases. In this study the duration of STRIDE in HH was significantly shorter in slow walking, which can be attributed to the shortening of the steps. This primarily acts as an adaptation mechanism, manifesting through the shift of the COM and the increased height of the heel [22]. Shortening the step is thus considered a preventative measure to prevent instability or even falls [11].

The economy of walking requires the speed of steps to equal the oscillations of a pendulum whose length is given by the length of the limbs. According to a previous study [23], taller individuals demonstrate longer steps with slower cadency. The central nervous system as well as logistical cardiovascular elements are important for walking, too. Slow walking speeds exert more load on the postural system, and that is why fatigue occurs earlier in longer and slower walking than in medium speed walking. In addition, walking in HH requires stability in the STANCE phase. Stability is achieved at optimum walking speed. In a pilot study, a speed of less than 0.5 $m.s^{-1}$ caused problems with balance, and therefore we recommend non-experienced HH wearers to walk at speeds higher than 0.5 $m.s^{-1}$.

The required energy expenditure is determined by the mass in motion and the extent of the COM movement along the x-axis (anteroposterior direction), y-axis (horizontal plane), and z-axis (vertical plane) from its original position. Walking that requires minimal energy expenditure is typically considered normal walking. [24-26]. The energy demands of walking in HH increase with decreasing walking speed [1]. The increased frequency of steps per minute resulting from wearing HH (confirmed by our study done at the same walking speed in HH and FS) meant higher energy demands while walking.

The limits of this study include using a constant walking speed where regard was not given to the optimal walking speed of individual participants. Certain differences can also occur between walking in a natural environment vs. on a treadmill, where the fine-tuning parameters of the movements are typical of walking change. This needs to be considered when generalizing the results and applying them to real life [6]. A homogeneous sample of healthy females with the same experience, i.e. the occasional wearing of HH, is a positive aspect of the research design. Considering the experimental conditions outlined in this research (v_1 and v_2, occasional wearers of HH, and 7 cm heels), it can be concluded that during slow walking, wearing HH shortens the phases of the gait cycle compared to FS. The walking pattern thus changes as a result. This therefore results in an increased frequency of steps per minute, which in turn means that such walking is energetically demanding.

Conclusions

The use of HH causes changes in the time and dynamic parameters of the gait cycle during slow walking. Due to HH, the duration of STANCE and STRIDE is shortened at the speed of v_1=0.97 $m.s^{-1}$ and at speed v_2=0.56 $m.s^{-1}$. SWING duration was shortened only in v_1.

The present study offers new knowledge on slow and very slow walking in HH in a group of inexperienced HH wearers. Based on our findings, we can say that the influence of HH causes changes in the gait cycle during slow walking. Despite HH causing significant changes in terms of shortening the individual phases of the step cycle, it is interesting that the ratio between STANCE and SWING was consistent in both HH and FS, at v_1 64/36 and at v_2 66/34. However, we can confirm that even slow walking speeds in HH alter the temporal parameters of the step cycle (there are more steps, and they last for shorter durations), thereby affecting the naturalness of walking.

Future research aims to offer personalized recommendations for inexperienced HH users in particular women's professions, thereby addressing their natural environments and typical walking speeds. Additionally, subsequent phases of the study would be enhanced by including a sample of experienced and regular female wearers of HH. Of course, the best recommendation is not to wear high heels, but this is not very realistic nowadays for some job positions [27]. Therefore, it would be appropriate to implement knowledge about walking into practice through trained physiotherapists or university students, who could conduct education in such workplaces.

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Artificial intelligence (AI) was not used in the creation of the manuscript.

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