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Effects of heel height and high-heel experience on foot stability during quiet standing

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ABSTRACT

Background: The use of high-heeled shoes (HHS) introduces instability into the wearer's balance system but how high-heel experience might influence standing balance is less examined in literature.

Research question: (1) Does foot stability decrease in both the antero-posterior (AP) and medial-lateral (ML) directions with increasing heel height during quiet standing?

(2) Does high-heel experience improve the wearer's foot stability during quiet standing in high-heeled conditions?

Methods: Twenty-four young females (12 regular and 12 non-regular HHS wearers) were recruited to perform quiet standing while wearing shoes with heel heights of 1 cm, 5 cm, 8 cm and 10 cm. The effects of heel height on the mean center of pressure (COP), their variability (standard deviations) and mean COP velocities in both the AP and ML directions were analysed by one-way repeated measures ANOVA and Bonferroni post-hoc test. The effects of high-heel experience were analysed through independent samples t-tests.

Results: The variability of the COP in both directions increased with heel height, although significance was found only in the ML direction. The COP velocities in both directions were highest for the 1 cm heel, decreased as the heel increased to 8 cm and increased again for the 10 cm heel. Experienced HHS wearers exhibited significantly smaller COP variances (AP) for the 8 cm and 10 cm heels, smaller COP velocities (AP) for all heels, and smaller COP variances (ML) and COP velocities (ML) for the 10 cm heel.

Significance: The use of HHS results in greater stability distortions in both AP and ML directions but high-heel experience improves balance control under high-heeled conditions. Our findings enhance the understanding of how high-heel experience might influence standing balance in different heel height, and highlights the importance of the ML components of the in-foot COP measures in the examination of standing balance in HHS.

1. Introduction

Upright standing is one of the most common daily tasks. However, maintaining balance in a standing posture is a complex mechanism and involves input from and interaction among the visual, vestibular and somatosensory sensory systems to coordinate joints and muscle groups across the entire body. When standing upright, an individual oscillates constantly as a combined result of hip and ankle motor strategies. While the dominant control of body balance in the medial-lateral (ML) direction is under the control of the hip abductors and adductors; the ankle strategy is the dominant strategy in the antero-posterior (AP) direction [1]. It is the primary strategy adopted when the disturbance to balance is small and the support base is firm. An individual tends to shift to the hip strategy in more unstable conditions [2]. The ankle strategy involves a small range of motion but considerable ankle muscle strength [3,4]. Therefore, the ankle movements are crucial to maintain standing balance.

High-heeled shoes (HHS) place the feet in a more plantar-flexed [5] and supinated position [6,7]. This limits the range of motion (ROM) of the ankle joints and hence can affect the efficiency of the ankle strategy for postural control. Additionally, the use of HHS changes numerous variables that affect the stability of the body's equilibrium, such as the height of the centre of mass (COM) [8] and the position of the centre of pressure (COP) relative to the support base as well as the form and size of the support base [9,10]. Studies have shown that wearing HHS with heels greater than 7 cm clearly worsens balance [3,11], decreases walking stability and increases the risks of falling [12] and ankle injuries [13,14].

Most studies examining HHS focus on the kinetics, kinematics, and muscle activity of gait, few have evaluated the effect of heel height on

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static balance. Earlier studies [3,15] compared standing balance of young female in bare feet and wearing HHS with a 7 cm heel by analysing the oscillation of the COP and found that standing balance was significantly worse in 7 cm HHS. Recent studies [11,16,17] expanded the testing conditions to include the 10 cm heels and found that standing balance was significantly worse for this heel height. However, standing balance evaluated in the sensory organization test in Hapsari and Xiong's studies [11], referred only to the AP direction, while the studies carried out by Truszczyńska et al. [16] and Mika et al. [17] focused only on non-regular HHS wearers.

Indeed, HHS experience might be another intrinsic factor that affects a person's postural control ability. Previous research suggested that prolonged use of HHS introduces biomechanical accommodations such as shortening of the calf muscles [18] and gastrocnemius medialis muscle fascicles and increased Achilles tendon stiffness [19], which might affect the efficacy in using the ankle movements in maintain balance, and thus resulting different balance strategies. However, most studies examining HHS experience have focused on gait [5,18,20–22], the effect of HHS experience on standing balance has remained mostly unexplored.

Because the mechanisms that govern standing and walking are significantly different [1,23], the effects of heel height and HHS experience on standing balance must be addressed separately. While the ankle plantarflexors and dorsiflexors control the body balance in the AP direction, ankle evertors and invertors govern the foot stability in the ML direction. To evaluate the instability introduced to the foot due to the increased heel height and reduced width of the heel base in HHS, in-foot COP variables could be evaluated.

This study investigated the effects of heel height (1 cm, 5 cm, 8 cm, and 10 cm) and high-heel experience on foot stability during quiet standing by analysing the COP oscillations and velocities in both the ML and AP directions. We hypothesize that foot stability decreases in the ML and AP directions with increasing heel height and that HHS experience improves the wearer's foot stability in high-heeled conditions.

2. Methods

2.1. Participants

Young female subjects (12 regular HHS wearers and 12 non-high-heeled shoe wearers) aged 21–28 years were recruited for the experiment. Regular HHS wearers were defined as those who had worn HHS with a minimum heel height of 5 cm three or more times per week and at least 18 h weekly in the past two years. Non-regular HHS wearers were subjects having some but limited experience in wearing HHS and had worn HHS less than once per week [11,16,17]. All subjects had foot sizes of EU 37 or 38 and were self-reported to be free from lower-extremity pain and injury for a minimum of one year prior to the study. All participants gave informed written consent prior to the experiment. Table 1 summarizes the demographic data of the participants.

2.2. Shoe samples

Sample shoes with heel heights of 1 cm, 5 cm, 8 cm and 10 cm were used in the study. This combination encompasses the most commonly worn heel heights in daily use. Being manufactured by the same manufacturer, the shoe styles and shoe sole materials of all shoes were kept the same (Fig. 1a) to minimize variance that might contribute to the measured variables. Except for the 1 cm heel shoes, all experimental shoes were dress shoes with pump heels. The dimensions of heel base were 5.3 cm in width and 7.3 cm in length for the 1 cm heel, and 1.2 cm × 1.2 cm for other heeled conditions (Fig. 1b). All shoe samples have a pointed toe box, and their sizes ranged from EU 36 to 38.

Table 1
Demographic data of the participants.

	Regular HHS wearers (Mean ± S. D.)	Non-regular HHS wearers (Mean ± S. D.)	p-values
Age (years)	24.6 ± 2.1	23.2 ± 2.3	0.169
Body height (cm)	159.0 ± 3.8	160.5 ± 4.7	0.441
Body mass (kg)	52.53 ± 6.94	49.15 ± 4.15	0.063
BMI (kg/m^2)	22.57 ± 2.63	21.32 ± 1.22	0.080

2.3. Equipment

The plantar pressure measurements were recorded using the Pedar®-X insole measuring system (Novel GmbH, Munich, Germany). A pair of 2 mm thick Pedar® insole sensors (EU size 36/37) with 99 pressure sensors embedded in each were used in the study. These insoles were calibrated prior to the experiment using a standard protocol. Measurements were recorded at a frequency of 50 Hz.

2.4. Experimental protocol

The recruited subjects were required to perform a double-leg quiet stance for each heel height during the experiment. The experimental protocol was approved by the University's Human Subjects Ethics sub-committee.

Prior to the experiment, a shoe-fitting session was performed to identify the best-fitting shoes for each testing condition. Subjects were provided sufficient time to try on different shoe samples (with the Pedar® insole sensors inserted) and were asked to walk around to ensure no heel slippage during push off.

The four testing conditions were assessed in random order. A two-minute rest was provided between each condition to prevent fatigue. For each condition, subjects were required to wear the HHS samples with the Pedar® insole sensors inserted and were required to perform the standardized quiet standing posture, which consisted of standing still with the feet 17 cm apart from the heel centres and a toe-out angle of 14°, arms by the subjects' sides, and eyes looking at a visual target placed approximately 3 m in front at eye level [24]. The COP measurements were recorded in three 30 s trials [25].

2.5. Data processing and analysis

The location of the COP was described as a pair of coordinates (COPx, COPy), with the x-axis going through the most posterior point that bisects the heel, and y-axis touches the most medial point at the forefoot area of the insole sensor. Increasing x-coordinate indicated a more lateral position and increasing y-coordinate indicated a more anterior position.

In this study, the mean COPx and COPy values, their standard deviations (which describe the variability of the COP) and the mean velocities of the COP in the ML (x-direction) and AP (y-direction) directions of the right foot were - calculated- for each 30 s quiet stance trial. The mean values of three trials for the same heel height of each subject were calculated and analysed in IBM SPSS v21. The effects of heel height on these six variables were examined by one-way repeated measures ANOVA (RANOVA), followed by the Bonferroni post-hoc test for pairwise comparisons. The effects of HHS experience were assessed by comparing the means of the two subject groups using independent samples t-tests. The mean difference was considered statistically significant if $p < 0.005$.

3. Results

3.1. Effect of heel height

The results of the one-way RANOVA (Table 2) describe an overall significant difference ($p < 0.005$) between the four heel conditions for all the six measured variables except for the S. D. of COPy. The results

Fig. 1. (a) Side view of the shoe samples (EU 38), and (b) size of heel base used in heeled shoes (left) and 1 cm shoes (right).

Table 2
Summary of RANOVA results for the effect of heel height on static stability.

Variables	F	df	p	η^2
Mean COPx	32.04	2.07	**0.000**	0.58
Mean COPy	57.91	1.71	**0.000**	0.71
S. D. COPx	7.47	2.33	**0.001**	0.25
S. D. COPy	2.06	3	0.114	0.08
Mean COPx Velocity	6.41	3	**0.001**	0.22
Mean COPy Velocity	7.77	3	**0.000**	0.25

Note: Significant values ($p < 0.05$) are shown in bold.

of Bonferroni pairwise comparisons (Fig. 2(a) and (b)) showed that significant differences were identified for each comparison of mean COPx and mean COPy. In general, the values of COPx decreased as the heel height increased, i.e., the COP shifted medially with increasing heel height. Compared with that in the 1 cm flat-heeled condition, the mean of COPx shifted medially by 1.41 mm in the 5 cm, by 3.62 mm in the 8 cm, and by 4.66 mm in the 10 cm heel conditions. The mean of COPy increased as the heel height increased, which means that the COP shifted forward as the heel height increased. Compared with the value for the 1 cm heel, the mean of COPy shifted anteriorly by 10.51 mm with the 5 cm heel, by 26.47 mm with an 8 cm heel, and by 36.76 mm with a 10 cm heel.

The mean S. D. of both COPx and COPy generally increased with heel height. However, significant differences were identified only in the ML direction (Fig. 2(c) and (d)). The mean S. D. of COPx was the lowest for the 1 cm flat-heeled condition (S. D. $COPx_{1cm} = 0.53$). A 3.8%, 26.4% and 64.2% increase was recorded for the 5 cm (S. D. $COPx_{5cm} = 0.55$), 8 cm (S. D. $COPx_{8cm} = 0.67$), and 10 cm (S. D. $COPx_{10cm} = 0.87$) heels respectively. Significant differences were observed between the 5 cm and 8 cm pair, and results of the 10 cm heel were significantly different from all the other heels. The increase of the mean S. D. in the AP direction was relatively small. Compared with the lowest value for the 1 cm heel (S. D. $COPy_{1cm} = 4.17$), only 1.9%, 3.8%, and 19.7% increases were observed for the 5 cm (S. D. $COPy_{5cm} = 4.25$), 8 cm (S. D. $COPy_{8cm} = 4.33$) and 10 cm (S. D. $COPy_{10cm} = 4.99$) heels, respectively.

The mean velocities of the COP in both directions (Fig. 2(e) and (f)) were highest and significantly different for the 1 cm heel (COPx $velocity_{1cm} = 5.99$ mm/s; COPy $velocity_{1cm} = 26.57$ mm/s). These values decreased as the heel height increased to 5 cm (COPx $velocity_{5cm} = 5.19$ mm/s; COPy $velocity_{5cm} = 21.11$ mm/s) and were the lowest for the 8 cm heel (COPx $velocity_{8cm} = 4.95$ mm/s; COPy $velocity_{8cm} = 18.87$ mm/s). They increased again when the heel height reached 10 cm (COPx $velocity_{10cm} = 5.50$ mm/s; COPy $velocity_{10cm} = 22.77$ mm/s).

3.2. Effects of HHS experience

The results of the independent samples t-tests (Table 3) showed no significant differences between regular and non-regular HHS wearers for the 1 cm and 5 cm heels in all variables except for the mean velocity of COPy, for which significantly smaller values were identified in regular HHS wearers for all heel heights. Significantly smaller values were also acquired from regular HHS wearers for the mean S. D. of COPx ($p = 0.043$) and mean velocity of COPx ($p = 0.012$) with the 10 cm heel and the mean S. D. of COPy with the 8 cm ($p = 0.047$) and 10 cm ($p = 0.009$) heels. Because smaller variability of the COP and lower COP velocity are often viewed as an indication of better static stability, the results suggest that HHS experience might help maintaining foot stability in HHS.

It is notable that HHS experience does not always improve foot stability. Under the 1 cm flat-heeled condition, the S. D.s of both COPx and COPy for regular HHS wearers were larger than those of non-regular HHS wearers (Fig. 3), although the differences were not statistically significant. When separately examining the trends for the S. D. of the COPx for regular and non-regular HHS wearers, it was found that non-regular HHS wearers had the smallest value and thus the best static stability for the 1 cm flat-heeled condition. COP variability increased with heel height, and the highest value was identified for the 10 cm heel condition, which represented a 129.5% increase in the ML direction and a 66.9% increase in the AP direction when compared with the values for the 1 cm heel. The changes of the S. D. values due to heel height were much smaller for regular HHS wearers.

4. Discussion

This study evaluated the effects of heel height and high heel experience on standing balance in the AP and ML directions. The four tested conditions cover the range of HHS using heel heights that are the most commonly worn in daily use. Our results showed that during quiet standing, the COP values shifted medially and anteriorly as heel height increased. This finding is largely consistent with many previous studies on forefoot loading related to the use of HHS [26–28]. Variability of COP (standard deviations of COP) in both the ML and AP directions generally increased with increasing heel height, but the main effect of heel height was found significant only in the ML direction. The S. D. of COPx for the 10 cm heel was significantly higher than all lower heel conditions. This result indicates increased instability in the ML direction as heel increases and suggests that higher muscle activities of the ankle invetors and evertors might be required to stabilize the ankle

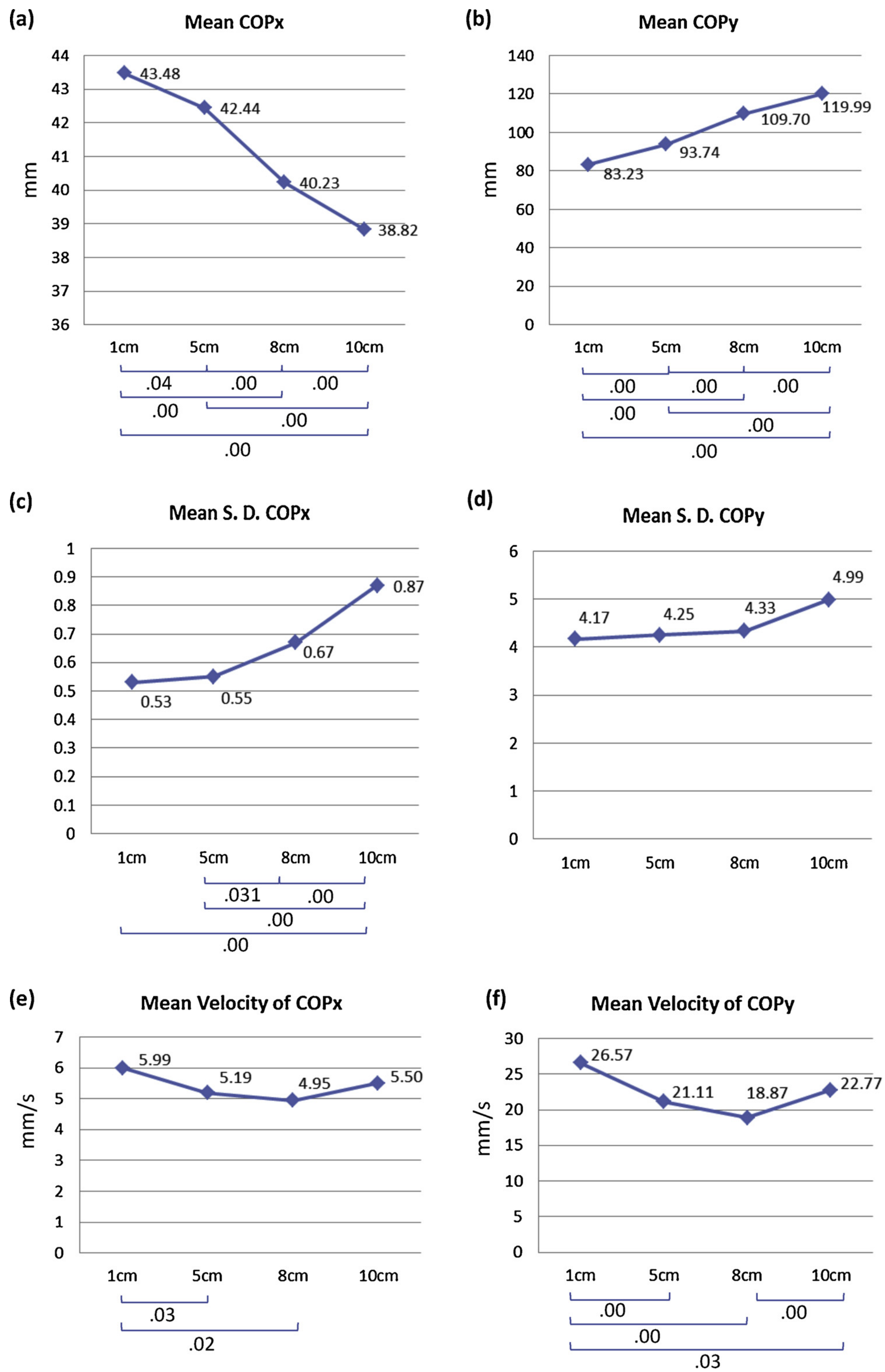

Fig. 2. The mean values of (a) COPx, (b) COPy, (c) S. D. COPx, (d) S. D. COPy, (e) velocity of COPx, and (f) velocity of COPy for all of the subjects. Significant differences ($p < 0.05$) were observed for each comparison in the Bonferroni post hoc test.

joint when standing in HHS [29]. Indeed, higher muscle activations of peroneus longus (one of the primary evertors) and tibialis anterior (primary dorsiflexor and invertor) had been associated with the use of HHS [5,13]. Because the effects of heel height were not statistically significant in the AP direction, this observation only partially confirmed our first hypothesis that foot stability decreases with increasing heel height in both directions.

The instability introduced by HHS can be explained by the increase in height of the COM as well as the reduction in support base area [8]. When standing in HHS, the COM is shifted upward and forward, resulting in a less stable balancing model. For aesthetic reasons, HHS always come with a narrow heel base, which fails to supply stable plantar support [8] to the wearer and makes postural control challenging. In addition to the changes in the COM and support base, the feet are more supinated and plantar-flexed when standing in HHS. These alterations to foot posture not only change the weight-bearing

Table 3
Mean, S. D., and mean velocity of COPx and COPy for regular and non-regular HHS wearers and the results of independent sample t-tests. Bold values indicate significant differences at $p < 0.05$.

	Heel (cm)	Non-regular HHS wearers		Regular HHS wearers		Mean differences	p-values
		Mean	S. D.	Mean	S. D.	(I-J)	
Mean COPx (mm)	1	44.00	2.73	42.88	3.73	1.11	0.434
	5	42.51	2.58	42.09	2.73	0.42	0.714
	8	40.43	2.52	40.18	2.35	0.25	0.813
	10	38.87	3.16	38.81	2.56	0.06	0.962
Mean COPy (mm)	1	81.14	18.34	88.64	13.22	−7.50	0.284
	5	93.67	17.14	97.07	12.62	−3.40	0.602
	8	107.31	10.04	111.79	9.21	−4.49	0.288
	10	118.04	13.15	122.41	7.18	−4.36	0.346
Mean S. D. COPx	1	0.44	0.23	0.62	0.33	−0.18	0.144
	5	0.58	0.22	0.51	0.23	0.07	0.467
	8	0.77	0.32	0.56	0.25	0.21	0.088
	10	1.01	0.42	0.73	0.24	0.28	**0.043**
Mean S. D. COPy	1	3.59	1.67	4.74	2.10	−1.15	0.181
	5	4.54	2.25	3.96	2.22	0.58	0.525
	8	5.13	2.23	3.52	1.34	1.60	**0.047**
	10	5.99	1.94	3.99	1.56	2.00	**0.009**
Mean COPx velocity (mm/s)	1	6.71	2.23	5.28	1.29	1.43	0.097
	5	5.61	1.15	4.84	1.24	0.77	0.168
	8	5.40	1.22	4.49	0.97	0.91	0.081
	10	6.00	0.81	4.94	0.88	1.06	**0.012**
Mean COPy velocity (mm/s)	1	30.88	10.29	22.37	6.54	8.51	**0.040**
	5	23.97	5.35	18.45	4.96	5.52	**0.028**
	8	21.,71	4.92	16.06	3.68	5.65	**0.009**
	10	26.56	4.50	18.66	4.07	7.89	**0.001**

conditions of the feet [8,25,26] but also reduce the ROM of the ankle in plantar flexion and calcaneal eversion. Hence, the feet might not be able to evert as naturally and efficiently to maintain balance as heel elevation increases [14]. The collective result might be a different balance strategy that uses different amounts of hip and ankle motor activity to maintain body equilibrium. During quiet standing, the ankle strategy is the first strategy adopted to counteract small perturbations of the centre of gravity. As the instability increases with heel height, larger perturbations of the centre of gravity might occur. The hip strategy is adopted if the ankle strategy fails to maintain balance, especially when the ROM of the ankle joints is restricted in HHS. This explanation is supported by the work of Hapsari and Xiong, in which more hip strategy was used when standing in HHS, although the ankle strategy was still predominantly adopted [11].

It is also interesting that although variations to the COP in flat-heeled condition were the lowest, the mean COP velocities were the highest. This observation suggested that under the flat-heeled conditions, standing balance was maintained using minor but high-frequency regulating adjustments at the ankle joints. As heel height increased to 8 cm, the COP oscillation was larger but slower, indicating a less stable standing posture and that corrective movements were applied accordingly. When the heel height reached 10 cm, both the magnitude and velocity of the COP increased. Larger COP oscillations and more rapid rate of change of COP movement indicate poor standing stability. Greater effort and more intensive corrective movements from both ankle and hip were thus adopted to maintain body balance.

In disagreement with Hapsari and Xiong's findings that HHS experience had no significant effect on standing balance [11], this study showed statistically significant effects of HHS experience on standing balance in both the ML and AP directions, especially in high-heeled (8 and 10 cm) conditions. This result affirmed our second hypothesis that HHS experience improves the wearer's foot stability during high-heeled conditions. Moreover, significantly lower COP velocities were observed for regular HHS wearers in the AP direction for all heel conditions, suggesting that they might have better muscle strength in their anterior and posterior postural muscles, allowing a more efficient balance

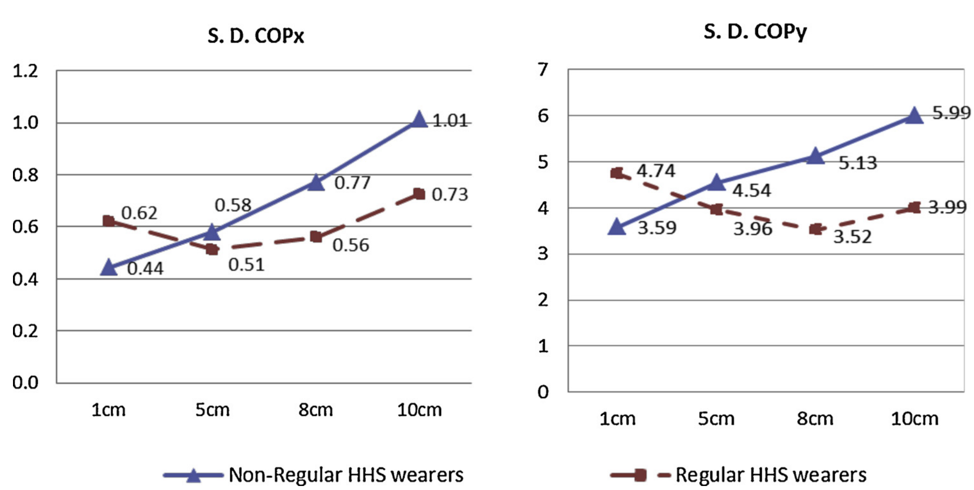

Fig. 3. Mean values of S. D. COPx (left) and S. D. COPy (right) for regular and non-regular HHS wearers.

strategy to be adopted when wearing HHS. This explanation is supported by previous EMG studies [5,11] in which experienced HHS wearers were found to exert different muscle effort from certain lower extremity muscles.

In addition, although regular HHS wearers generally have better foot stability than non-regular HHS wearers for high-heeled conditions, their HHS experience does not appeared to help minimising COP oscillations in low-heeled conditions. This observation might be explained by chronic adaptations in the muscle-tendon architecture of regular HHS wearers. As suggested in some studies [18,19], the shorter calf muscles and stiffer Achilles' tendon observed in experienced HHS wearers may help maintaining the tension in the plantarflexor muscle-tendon unit during standing, thus improving the force transmission and proprioception when wearing HHS.

This study has several limitations. Due to the demographic characteristics of the participants recruited, the results of this study are valid only for young healthy female subjects. The definition of a regular HHS wearer adopted in this study might also alter the results regarding the effects of HHS experience.

5. Conclusion

The use of HHS decreases postural stability during quiet standing, and COP variations in both the AP and ML directions increase with heel height. Adverse effects are accentuated when the heel height reaches 8 cm and become even worse at 10 cm. However, high heel experience helps maintaining postural control in high-heeled conditions. Non-regular HHS wearers should avoid occasional use of HHS with heels higher than 8 cm. Our findings enhance the understanding of how in-foot COP vary with heel height in both the ML and AP directions during quiet standing, and how HHS experience might influence standing balance. The present study also highlights the importance of the ML components of the in-foot COP measures in the examination of balance in HHS.

Conflict of interest

The authors declare that they have no competing interests.

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