

Effect of high-heeled shoes on postural control in the upright and the leaning body stance

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Abstract

Objectives: The studies examining the high-heeled shoes effect use the typical model of upright quiet stance with no information about leaning stances. This study aimed to examine the effect of high-heeled shoes in the upright and the leaning stance.

Methods: The trajectory of the center of pressure (COP) was recorded (forceplate Kistler-9286AA, sampling at 100 Hz, software Kistler BioWare®-2812A1, v.3.2.6) in 11 young women (22.14 ± 2.93 years, moderate users of high-heeled shoes) in the quiet upright and the leaning stance (forward, backward, rightward, leftward rigid body leaning). The participants were tested barefoot (BF) and with two high-heeled shoes (heel height-HH: 6.5 cm and 11 cm). In the upright stance, the anterior-posterior and the medial-lateral COP path (cm) and COP range (cm), respectively, were determined. In the leaning stance, the COP displacement (cm) and the COP range of stability (% of BS length and % of BS width) were determined. In each stance, a repeated measures ANOVA followed by HH pairwise comparisons were used for statistics ($p \leq 0.05$, SPSS 22.0).

Main outcomes and results: In the upright stance, the COP path was significantly increased ($p \leq 0.05$) in the high-heeled shoes compared to BF, as well as when the HH was increased. The COP range was not significantly altered ($p > 0.05$). In the leaning stance, both the COP displacement and the COP range of stability were significantly altered ($p \leq 0.05$), with a directional sensitivity of the significant alterations in the COP range of stability.

Conclusions: The high-heeled shoes induce COP alterations which indicate a worsening of postural control in both the upright and the leaning stance, with a directional sensitivity in the leaning stance. Thus, the body positions that challenge postural control more than the typical upright stance should be also included in relevant studies.

Abbreviations: COP: Center of Pressure, HH: Heel height, BF: Barefoot, BS: Base of support, COM: Center of mass.

Introduction

The high-heeled shoes induce substantial noise in the process of postural control as they cause not only a reduction of the base of support (BS) but also shift upward the body center of mass (COM) [1,2]. Furthermore, the long-term wearing of high-heeled shoes is associated with muscle imbalance and instability around the ankle joint, a condition that increases the predisposition to an ankle sprain [3] and a fall incidence [4]. Thus, for an optimum body balance, the shoe heel height should range from 3 to 5 centimeters [4,5].

The reduced postural control due to high-heeled shoes is evidenced in the significantly altered trajectory of the center of pressure (COP) [6-9]. In the relevant studies, the position of the upright quiet stance is typically used [6-9] with a lack of research information about leaning stances. In body leaning, the COM is shifted closer to the BS limits; thus, the postural control system operates at the borders of postural balance [10] where stability is achieved through a different strategy than the upright quiet standing [10-12]. In the quiet upright standing, the ankle (or the hip) strategy is used, whereas, the leaning stance brings the body at the border between the ankle and the stepping strategy [10-11]. In a rigid body leaning stance, the fast detection of the border between the ankle and the stepping strategy is crucial for postural stability [10-11]. The detection of the border between the ankle and the stepping strategy may become more difficult when wearing high-heeled shoes as the

COM is moved closer to the BS limits (closer to the postural stability limits). The leaning stance is an established biomechanical model for testing postural balance [10,11,13], with some studies even questioning the appropriateness of using quiet stance as a general model of postural control [13,14]. Thus, this study aimed to examine the effect of high-heeled shoes on postural control in the upright and the leaning body stance.

Methods

Participants

Eleven young women (Age: 22.14 ± 2.93 yrs, Height: 1.63 ± 0.04 m, Weight: 52.44 ± 6.94 kg, BMI: 19.85 ± 2.99 kg/m²) participated in the study. The age of the young women was within the age range (20 to 29 years old) that the highest rate of injuries due to the use of high heel shoes is reported (34.2% of cases from 2002 to 2012 [15], and 33.4% of cases from 2006 to 2010 [16]). Their anthropometric characteristics

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[17] and their high-heeled shoes wearing experience [7,8] are reported to affect postural control. Thus, with regard to body height, body mass and foot length, the inclusion criteria aimed to a body height range from 1.60 m to 1.70 m, a normal BMI ($18.50 \text{ kg/m}^2 - 24.99 \text{ kg/m}^2$) and participants who wore a 37 European shoe size (6.5 United States shoe size). With regard to the high-heeled shoes wearing experience, our participants wore shoes with heel height greater than 4 cm and less than 10 cm from 1 to 2 times a week, for 5-6 hours per day. Their wearing experience may be considered as moderate high-heeled shoes experience [7]. All participants had normal vision and hearing, and they were all free of any medical issue that would potentially influence postural stability. A written informed consent was obtained from all subjects. All experimental procedures were in accordance with the research policy of the School of Physical Education and Sports Science, National and Kapodistrian University of Athens, Greece.

Procedures

A force plate (60 cm × 40 cm × 3.5 cm, Kistler Type: 9286AA, Switzerland, sampling rate at 100 Hz, BioWare® data acquisition and analysis software-Kistler 2812A1, version 3.2.6.) was used to collect the COP trajectory data during two stance tests, the upright (quiet standing) and the leaning stance (Figure 1). Two trials were performed in each task with two minutes rest between trials.

Both the upright and the leaning task were performed barefoot (BF) and at two heel height (HH) conditions: with a shoe of 6.5 cm HH, and with a shoe of 11 cm HH (Figure 1). The order of each stance conditions was randomly assigned to the participants. To minimize any possible effect of the coefficient of friction [18] or footwear comfort [19] both shoes were similar in construction with the single exception of the HH. According to the HH classification in previous studies (Table 1), the 6.5 cm and the 11 cm HH of the present study may be classified as a medium and a high HH, respectively. As it is presented in Table 1, the previous studies report as high-heeled shoes those with a HH from 9 to 10 cm. Thus, the 11 cm HH used in the present study could also be classified as a very high HH.

In both the upright and the leaning stance, the participants were instructed to stand on the force plate, with feet comfortably spaced, their arms hanging at the side of their body. They were also asked to look at a circular target (diameter 3 cm) positioned in front of them at eye level and at a distance of 3.5 m. Sampling duration for upright stance was

Table 1. Heel base width and heel height classification as used in previous studies with young women

	Age (years)	Heel base width	Heel height (cm) [†]				
			BF ^{**}	Flat	Low	Medium	High
Gerber, et al. (2012)	18 - 30	1 cm x 1 cm	BF				7
Ko, et al. (2013)	20.9 ± 1.3	not reported		0.5	4		9
Kim, et al. (2013)	22.9 ± 1.5	not reported		0			7
Hapsari and Xiong (2015)	18 - 30	1.5 cm x 1.5 cm		1	4	7	10
Present study	22.1 ± 2.9	1 cm x 1 cm	BF			6.5	11

[†] the heel height classification as reported in each study. ^{**} BF: barefoot

chosen at 70 s [6-9]. In the leaning stance, the same instructions were provided while, in addition, the participants were further instructed to subsequently perform a forward, a backward, a rightward and a leftward maximum body lean, and to maintain each lean for 5 s [20]. Each body lean was performed as far as possible while maintaining a straight body line from heel to head, and both heels in contact with the force plate. Between each body lean directional change, the participants returned to the upright quiet position where they remained for 5 s. Based on pilot data collection, the total sampling duration for the leaning stance was 80 s.

The perimeter of the feet in the BF condition, as well as the perimeter defined by the sole and the heel of the shoe in the two HH conditions, was traced on a piece of paper placed on the top of the force plate. Thus, in every trial, each participant repositioned herself in the same place with regard to the force platform coordinates. The traced perimeter was used to define the dimensions of the base of support (BS) (Figure 2). The correct repositioning of each participant on the BS trace was carefully checked. The BS was measured at $27.73 \pm 2.07 \text{ cm}$, $27.71 \pm 2.07 \text{ cm}$ and $27.71 \pm 2.07 \text{ cm}$, for BF, for the 6.5 cm HH and the 11 cm HH, respectively. The BS width was significantly larger (paired t-test, $p \leq 0.05$) in BF than the 6.5 cm HH ($p = 0.040$) and 11 cm HH ($p = 0.040$) shoes, with no significant difference between the two shoes ($p > 0.05$). In the BF condition, the BS length was measured at $23.71 \pm 0.79 \text{ cm}$, while in the shoe condition the BS length was fixed at 22.5 cm and at 21 cm, for the 6.5 cm HH and the 11 cm HH, respectively. In the BF condition, the feet opening angle was calculated according to Chiari et al. [17] and was found at 11.28 ± 3.23 degrees, based on the distance between the two big toes ($14.55 \pm 3.36 \text{ cm}$) and the inter-malleolar distance ($9.86 \pm 2.89 \text{ cm}$). The variability (26.8%) of the feet opening angle is within the BS stance expected range which may be considered as a low foot opening angle variability [21]. To the best of our knowledge, no calculation method has been previously reported for the feet opening angle in a shoe wearing stance.

Data processing: In the upright stance, the variables determined were the COP path (cm) and the COP range (cm), in the anterior-posterior and the medial-lateral direction, respectively. In the leaning stance, the variables determined were the COP displacement expressed in cm, and the COP range of stability expressed as a percentage (%) of the BS dimensions. The forward, the backward, the rightward, and the leftward COP displacement (cm) was defined as the difference between the mean COP value during the 5 sec that the participant remained at the upright stance and the mean COP value during the 5 sec that the participant remained at each direction, respectively, of the leaned body position. For the calculation of the COP range of stability calculation, initially, the total anterior-posterior and the total medial-lateral COP displacements were estimated as follows: A) the sum of the maximum forward and the maximum backward COP displacement defined the total anterior-posterior displacement (displacement in the

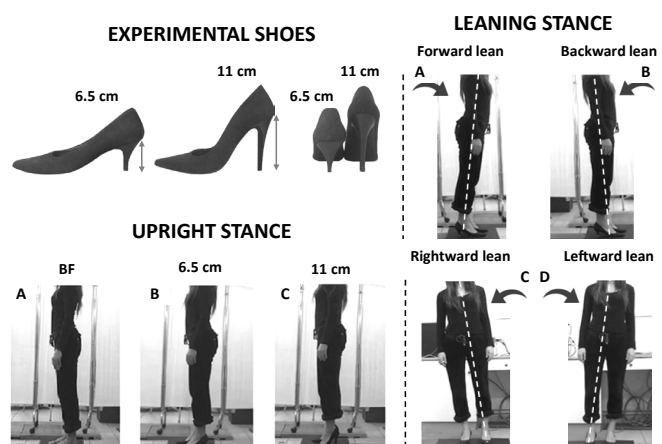


Figure 1. Left-Top: The two high-heeled experimental shoes (Medium HH: 6.5 cm, High HH: 11 cm). Left-Bottom: Upright stance in the barefoot (BF) and the high-heeled shoes (6.5 cm HH and 11 cm HH) conditions. Left: The forward (A), the backward (B), the rightward (C) and the leftward (D) leaning stance

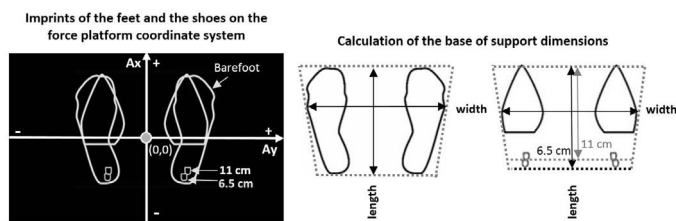


Figure 2. Left: Imprints of the feet and the shoes (heel height of 6.5 cm and 11 cm) with regard to the force platform coordinate system (Ax: anterior-posterior axis, Ay: medial-lateral axis, 0,0: origin point). Right: Schematic representation of the base of support and of the calculation of its length and width dimension

direction of BS length) and B) the sum of the maximum rightward and the maximum leftward COP displacement defined the total medial-lateral displacement (displacement in the direction of BS width). In continuance, two variables were defined for the COP range of stability, naming the anterior-posterior and the medial-lateral COP range of stability, expressed as a percentage (%) of the BS length and the BS width, respectively. In both the upright and the leaning stance, the value that inserted in the statistical analysis was the two trial average for each stance condition.

Statistical analysis

A repeated measures ANOVA were conducted separately for the upright and the leaning stance, with 3 levels of the repeated factor in each one (BF, 6.5 cm HH and 11 cm HH) to test the HH effect on the postural control variables. If the Mauchly’s test of sphericity indicated a sphericity violation, the Greenhouse-Geisser ($\epsilon < 0.75$) or the Huynh-Feldt ($\epsilon > 0.75$) corrections were used. If the HH main effect was significant, the pairwise comparisons with Bonferroni correction were tested between stance conditions. For the statistical tests, the level of significance was set at $p \leq 0.05$. Statistical analysis was carried out using IBM SPSS Statistics (Version 22.0).

Results

Figure 3 illustrates an example of the COP path in each HH condition with regard to the feet positioning on the force plate for a representative subject in the upright and the leaning body stance.

Upright stance: In the upright stance, a significant HH effect was found for the COP path in both the anterior-posterior ($F = 46.38, p = 0.000$) and the medial-lateral ($F = 11.22, p = 0.000$) direction (Figure 4). The HH differences with regard to the COP path were all significant, in both the anteroposterior and mediolateral direction ($p=0.000$ for all), except for the comparison between BF and the 6.5 cm HH in the medial-lateral direction (Figure 4). The HH effect was not significant for the COP range in both the anterior-posterior ($F=2.53, p=0.105$) and the medial-lateral ($F=1.02, p=0.379$) direction (Figure 4).

Leaning stance: In the leaning stance, a significant HH effect was found for the COP displacement during the forward ($F = 94.42, p = 0.000$), the backward ($F = 33.75, p = 0.000$), the rightward ($F = 8.96, p = 0.000$) and the leftward ($F = 25.97, p = 0.000$) body lean (Figure 5). The HH differences in the COP displacement were all significant in the forward and the backward lean ($p = 0.000$ for all). In the rightward lean, the difference was significant only between the BF and the 11 cm HH ($p = 0.010$) ($p = 0.089$ for BF versus 6.5, $p = 0.246$ for 6.5 cm HH versus 11 cm HH) (Figure 5). In the leftward lean, the difference was significant only between the BF and the 6.5 cm HH ($p = 0.000$), as well as between the BF and 11 cm HH ($p = 0.000$), but not between the 6.5 cm and the 11 cm HH ($p = 1.000$).

With regard to the COP range of stability, the HH effect was significant for both BS dimensions (BS length: $F = 102.65, p = 0.00, BS$ width: $F = 16.35, p = 0.00$) (Figure 6). The HH differences in the COP range of stability were all significant ($p = 0.000$ for all), except for the comparison between the 6.5 cm and the 11 cm HH ($p = 1.000$) with regard to the BS width ($p = 1.000$) (Figure 6).

Discussion

The purpose of this study was to examine the effect of high-heeled shoes on postural control in the upright and the leaning body stance. The assumption of the study was that, in both the upright stance and the leaning body position, the high-heeled shoes would cause a worsening of body balance, which would be more pronounced at increased HH.

In the present study, the postural control worsening was documented at the increase of the COP path in the upright stance and, the reduction of the COP displacement and of the COP range of stability in the leaning stance. The worsened postural control found in the present study is in agreement with previous studies [1,6-9]. When

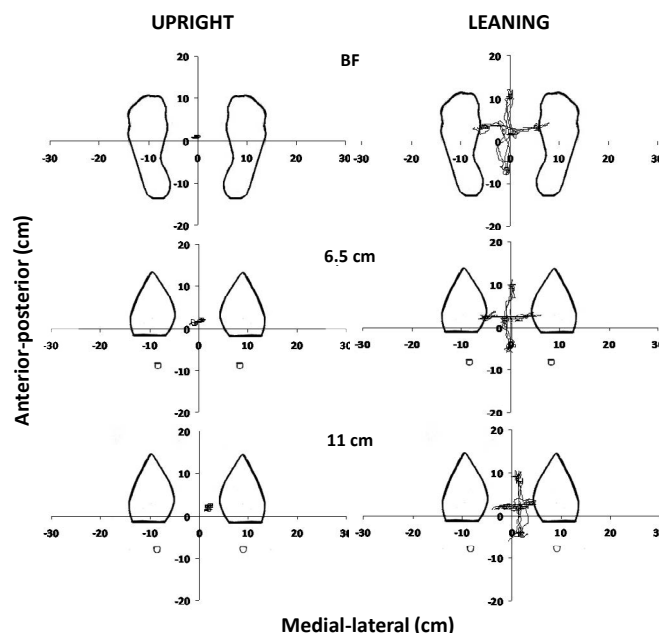


Figure 3. Schematic representation of the COP path of one subject with regard to the base of support, in the barefoot (BF) and the high-heeled shoes (6.5 cm HH and 11 cm HH) conditions, in the upright (Left) and the leaning (Right) stance. The anterior-posterior and the medial-lateral directions indicate the Ax and Ay, respectively axis of the force plate coordinate system

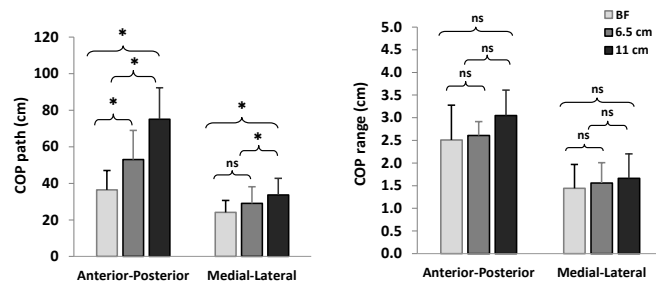


Figure 4. Mean (SD) of the COP path (Left) and the COP range (Right) in the upright stance, in the anterior-posterior and the medial-lateral directions, in the barefoot (BF) and the high-heeled shoes (6.5 cm HH and 11 cm HH) conditions. *significant pairwise difference between HH conditions at $p \leq 0.05$

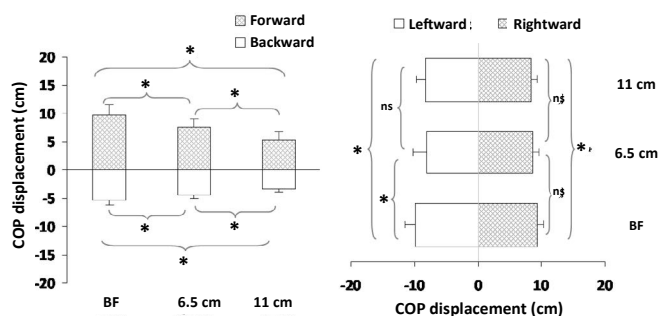


Figure 5. Mean (SD) of the leaning stance COP displacement, in the forward and backward lean (Left), as well as in the rightward and leftward lean (Right), in the barefoot (BF) and the high-heeled shoes (6.5 cm HH and 11 cm HH) conditions. *significant pairwise difference between HH conditions at $p \leq 0.05$

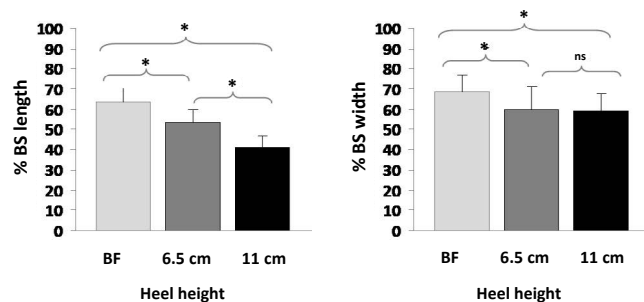


Figure 6. Mean (SD) of the leaning stance COP range of stability, expressed as a percentage (%) of the base of support (BS) length (Left) and BS width (Right), in the barefoot (BF) and the high-heeled shoes (6.5 cm HH and 11 cm HH) conditions. *significant pairwise difference between HH conditions at $p \leq 0.05$

wearing high-heeled shoes, the upward shift of COM [4] and the concomitant forward COP displacement [1,2] lead to changes of the foot joint configuration and in the muscle function around the ankle joint, that is the joint most proximal to the BS [2,22]. The change of the foot anatomical configuration towards an increased plantar flexion due to high-heeled shoes reduces the effectiveness of the ankle plantar flexors [22], thus hindering the optimal postural stability. The increased plantar flexion due to high-heeled shoes also induces modifications of the normal anatomical configuration [4] and the normal muscle function [4,22] in body areas distal to the BS. These distal modifications further hinder the postural control when wearing high-heeled shoes, and are associated with musculoskeletal pain [4,22].

In the relevant studies, the HH from 9 to 10 cm is typically classified a high heel condition [6-9]; nevertheless, there appear no distinct criteria of the HH classification as flat, low, medium or high. Furthermore, the width of the heel width base is not always reported [6-9], although it is considered as a critical parameter for postural stability [23]. In specific, the foot is more unstable with a small than with a large heel base as shown by the COP trajectories and the plantar pressure distribution in walking [23]. For an optimal foot functionality and the avoidance of harmful fatigue, the shoe HH should range from 3 to 5 cm (usually classified as low HH) [4,6-9]. However, in the present study, the 11cm HH was chosen as it is very popular among young women; in addition, its small heel base width (1 cm x 1 cm) indicates a very restricted BS. Thus, it was expected to impose a substantial challenge to postural control, particularly in the leaning body stance which inherently brings the COM closer the BS borders.

In the leaning stance, the significant reduction of the forward and backward COP displacement when HH was increased is in agreement

with previous studies [7]. The differences between the BF and the high-heeled conditions, as well as between the two HH, were all significant in both the forward and backward lean; however, this was not the case in the rightward and the leftward lean. This finding may be associated with the asymmetry of body weight distribution, as normal adults appear to load more their right foot for about 60% of their stance time [24], but it may also indicate a directional sensitivity of postural stability [25,26]. The directional sensitivity of postural control as a function of the BS geometry has been previously documented in dynamic and static conditions [26]. The postural stability during the upright tandem stance showed a 3-fold greater sensitivity in the medial-lateral direction (BS width) than the anterior-posterior direction (BS length) [26]. The reverse was observed in the typical upright stance, where the postural stability may be 2.3-fold greater in the anterior-posterior direction (BS length) than the medial-lateral direction (BS width) [26]. It is possible that, besides BS geometry, the directional sensitivity of postural control may also depend on the inherent closeness of the COM projection to the BS borders in the stance under examination (as in the case of high-heeled leaning), a situation that may alter the proprioceptive control of posture [25].

In the HH of 11 cm which is particularly popular among young women, the significant decrease of the COP stability range (64%, 56% and 41% of the BS length in the BF, the 6.5 cm HH and the 11 cm HH, respectively) underlines the reduction of the utilized BS length when wearing high-heeled shoes. The reduction of the utilized BS length when wearing high-heeled shoes may be associated with the proprioceptive detection of the transition border between the ankle and the stepping postural control strategy [10-12]. These two strategies involve different muscle synergies; thus, for a successful postural control, the fast detection of the transition border from one strategy to the other is of critical importance [10,11]. When compared to the upright stance, the leaning stance imposes an inherent noise to the postural control system due to the COM projection as closer as possible to the BS limits, or more accurately, as closer as possible to the border between the ankle and the stepping strategy [10-13]. In high-heeled compared to BF leaning, this inherent noise may be further accentuated, allowing the assumption of an enhanced difficulty to encode the border between the ankle and the stepping strategy. Besides the reduction of the utilized BS length, there was also a significant reduction of the utilized BS width in the high-heeled leaning compared to BF leaning, but not when the shoe HH was increased (71%, 61% and 60% of the BS width in the BF, the 6.5 cm HH and the 11 cm HH, respectively). In specific, the reduction in the utilized BS width (about 10 percentage points) appeared lower than the reduction in the utilized BS length (8 and 23 percentage points, respectively in the 6.5 cm and the 11 cm HH compared to BF, and 15 percentage points between the two HH). Overall, the utilized BS reductions may indicate a directional sensitivity of postural control, a concept that has been previously documented [26] and has been associated with situations that may alter the proprioceptive control of posture [25].

The comparison of the leaning stance results with previous studies is not easy as, to the best of our knowledge, no previous study appears to examine the HH effect in a rigid body leaning stance as the one used in the present study. Hapsari and Xiong [7] who used a task including body leaning in their protocol, also report that the HH increase (0 cm, 4 cm, 7 cm, and 10 cm) resulted to a significant postural control worsening, particularly when HH was increased more than 4 cm. However, the task used in the protocol of Hapsari and Xiong [7] was a complex task in which postural control (biomechanical stability) was a secondary function. In the task of Hapsari and Xiong [7], the

performance stability rather than the biomechanical stability was the primary function; furthermore, the leaning position was not a rigid body position, as their task could be performed with or without hip flexion. Both the upright quiet stance [11,12] and the rigid body leaning stance [10-13] are established models for testing the biomechanical stability of the postural control. The upright quiet stance is predominantly used in postural control studies; however, it should be noted that some studies question the appropriateness of the upright quiet as a general model of postural control [13,14].

Conclusion

In the present study, in both the upright and leaning stance, the COP alterations when wearing high-heeled shoes denote a postural control worsening which may be associated to a decreased postural stability and an increased falling risk. The postural control was further worsened when the HH was increased, with a directional sensitivity of the postural control in the leaning stance. One could claim that the lessening of wearing high-heeled shoes, or even the abolition of high-heeled shoes, could lead to an effective elimination of all the negative issues that arise from their use. However, despite the public warnings from institutions of occupational health [27] and international medical societies [28], it is possible that, for a presentable image or a formal office wear, employers may enforce to women a dress code that includes the daily long-hour use of high-heeled shoes [27-29]. The increasing prevalence of daily high-heeled shoes wearing is ascertained (from 39% up to 49% of the women population in the period for from 2003 to 2014) [28]. The 2-fold increase in the injury prevalence due to high-heeled shoes is also ascertained for the period from 2002 to 2012 [15,16]. Thus, the studies that highlight the acute or overuse injury risk potential due to high-heeled shoes are of critical importance. Such studies should include not just the typical model of upright quiet stance, but also body positions that challenge postural control and may provide indisputable evidence of the potential harmful implications of high-heeled shoes wearing.

Competing interest declaration

The authors declare that they have no competing interest.

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