

Full length article

Effects of high-heeled footwear on static and dynamic pelvis position and lumbar lordosis in experienced younger and middle-aged women



Jan Schroeder*, Karsten Hollander

Department of Sports and Exercise Medicine, Institute of Human Movement Science, University of Hamburg, Germany

ARTICLE INFO

Keywords:

High-heeled shoes

Lordosis

Spine

Back surface reconstruction

Posture

ABSTRACT

There is still conflicting evidence about the effect of high-heeled footwear on posture, especially if methodological confounders are taken into account. The purpose of this study was to investigate the effect of high-heeled footwear on lumbopelvic parameters in experienced younger and middle-aged women while standing and walking. Thirty-seven experienced younger ($n = 19:18\text{--}25$ years) and middle-aged ($n = 18:26\text{--}56$ years) women were included in this randomized crossover study. Using a non-invasive back shape reconstruction device (rasterstereography), static (pelvic tilt and lumbar lordosis angle) and dynamic (pelvic rotation, median lumbar lordosis angle and range of motion) parameters representing pelvis position and lumbar curvature were measured. In order to analyse standing and walking on a treadmill (0.83 m/s), the effects of high-heels (7–11 cm) were compared to standard control shoes. There were no effects on the lumbar lordosis angle or range of motion under static or dynamic conditions ($p > 0.05$, $d \leq 0.06$). But there was a small effect for a reduced pelvic tilt ($p = 0.003$, $d = 0.24$) and a moderate effect for an increased transversal pelvic rotation ($p = 0.001$, $d = 0.63$) due to high heel shoe standing or walking, respectively. There were no significant age-group or interaction effects ($p > 0.05$).

Altered pelvic parameters may be interpreted as compensatory adaptations to high-heeled footwear rather than lumbar lordosis adaptations in experienced wearers. The impact of these findings on back complaints should be revisited carefully, because muscular overuse as well as postural load relieving may contribute to chronic consequences. Further research is necessary to examine clinically relevant outcomes corresponding to postural alterations.

1. Introduction

While commonly used in the female population, high-heeled footwear affects posture and gait and is generally thought to be associated with back complaints [1]. High-heeled footwear has been shown to have various effects on foot pathologies like hallux valgus and musculoskeletal pain [2]. It seems obvious that there are alterations in alignment and motion patterns in the foot-ankle complex. Additionally, other authors have discussed various other 'chain reaction' kinematic effects superior to the ankle [3]. A popular hypothesized compensating strategy, and probably the one most frequently investigated, is that of increased lumbar lordosis [1].

There have been conflicting findings and scientific perspectives on the lumbar lordosis and it was shown that the effects of high-heeled footwear are dependent on the habituation to this footwear and the age of the participants [4–12]. Cowley et al. [13] concluded in their review that increased lumbar lordosis angles were found predominantly in inexperienced users.

Furthermore, there have been different methodological confounders leading to difficulties in comparing the published results. While some authors investigate static outcome parameters [3–7,9,11,12], some report dynamic outcomes [6,12,14,15]. In addition, the assessment tools differ between studies using low-dose whole body x-ray [3,5], inclinometers for indirect back surface reconstruction [11], lateral photogrammetry [7] or electromyography [15]. While radiographic assessments have the advantage of direct measurement of the spinal bones it has its disadvantages and ethical limitations due to the ionizing radiation [16]. The rasterstereographic assessment provides a safe and valid alternative that has been used for example in pregnancy [17] and in scoliosis progress-monitoring investigations [18]. Additionally, rasterstereography offers the opportunity for a dynamic spine shape assessment during gait [19,20].

Due to the persistent research gap concerning assessment tools, age and habituation, the aim of this study was to investigate the effects of high-heeled footwear by means of video rasterstereography on static and dynamic pelvis position and lumbar lordosis parameters in young

* Corresponding author at: Turmweg 2, 20148, Hamburg, Germany.

E-mail address: jan.schroeder@uni-hamburg.de (J. Schroeder).

and middle-aged females experienced in wearing high-heeled shoes. Despite conflicting evidence, we hypothesized high-heel associated increased lumbar lordosis angles accompanied by corresponding pelvis position adaptations compared to a standard shoe condition.

2. Methods

2.1. Study design

The present investigation had a randomized crossover design. After a preliminary familiarization, the participants went through three repeated measures: a baseline test followed by two measurements in a randomized order (control: standard shoe condition; experimental: high-heeled shoe condition). The baseline and the control condition were the same, and were performed twice to determine the repeatability. All measures were separated by ten minutes for shoe habituation (standing, walking, and sitting).

2.2. Subjects

Thirty-seven healthy women aged 18–56 years (age 27.7 ± 8.7 years, height 1.66 ± 0.06 m, weight 58.8 ± 7.8 kg, Body Mass Index 21.2 ± 2.3 kg/m² ranging from 16.5 to 27.4 kg/m²) were recruited from advertising in local newspapers. For analysis purposes, the sample was subdivided into a younger (≤ 25 y, $n = 19$) and a middle-aged (> 25 y, $n = 18$) group. Participants were informed about the study, the test protocol and the non-invasive character of the data assessment. The study was approved by the local ethics committee (ID: 662016) and participants gave informed consent prior to participation. The study was conducted and data were managed according to the Declaration of Helsinki in its current version.

Participants had to be used to high-heel shod walking for a minimum of three years with an average use of at least two hours per week (inclusion criteria). The presence of low back pain or any back pain history for the last two years served as exclusion criteria due to possible interfering effects on spine shape parameters [21].

High-heel exposure time was ranging between 2 and 50 h per week (13.9 ± 14.8) for a lifetime period ranging from 3 to 25 years (9.9 ± 5.5), and back pain was less than very weak (0.1 ± 0.3 pts.) in terms of a Borg pain scale [22] (Table 1).

2.3. Shoe conditions

To avoid interfering learning or disturbance effects, all participants used their own shoes. The footwear consisted of a pair of sport shoes with flat foam soles and a pair of high-heeled shoes with a recommended heel height between seven and eleven centimetres [4–6,9,10,12,15]. The average heel height was 8.7 ± 1.4 cm.

2.4. Instruments

2.4.1. Rasterstereography

Spine shape was analysed by video rasterstereography (Formetric®-System, Diers, Schlagenbad, Germany), a non-radiating device for an

indirect and high resolution (10 pts./cm²) back shape reconstruction (absolute error 0.2–0.5 mm) [23]. Specific back surface landmarks – like the vertebra prominens, the superior part of the rima ani representing the sacrum point, and the right and left lumbar dimple representing the positions of the posterior superior iliac spine – were recognized automatically to build up a Cartesian coordinate system. This coordinate system served as a body fixed calibration reference frame for a three-dimensional surface reconstruction. The distance between every point on the back surface and the optical system is calculated using triangulations (skin, projection lines, and camera). Based on every single point on the surface and its neighbour points video rasterstereography is able to provide a 3D frontal plane picture with convex, concave, or saddle-shaped areas. Thus, spinal bones beneath the skin surface can be detected. In combination with biomechanical modelling the geometry of vertebral bodies and pelvis bones can be calculated (position and direction). Consecutively, the shape of the vertebral column can be animated with its frontal, sagittal and transversal plane characteristics [23].

For static spine shape assessment, pictures were taken over a time period of 5 s (sample rate 10 frames/s) with an averaging procedure to eliminate postural sway effects. Pelvic tilt (PT°) and lumbar lordosis angle (LA°) served as highly reliable outcome variables (ICC > 0.95 , SEM $< 1^\circ$) in the sagittal plane [24]. For a better understanding of geometry, corresponding anatomical landmarks and subsequently derived spine shape parameters are illustrated (Fig. 1).

A conventional treadmill (Type Omega 2, Horizon Fitness, Lahntal, Germany) with a rope belt height of 15 cm was used in combination with the Formetric®-System in order to assess spinal curvature while walking. According to experiences from a pilot study, walking speed was set at 0.83 m/s with no inclination.

Spine shape was recorded for 5 s – representing approximately 5 double gait cycles – with a five-fold higher sample rate (50 frames/s) during treadmill walking. Dynamic outcomes reflected the sagittal plane lumbar angle range of motion covering all (left and right) double gait cycles (LA_ROM°). Based on this range of motion, the median lordosis angle (MLA°) was calculated representing the central tendency of all 250 sampled lordosis angle values during the observed gait cycles. Additionally, the range of pelvic rotation was examined describing motions in the transversal plane (P_ROT°). Reliability (ICC) for the dynamic variables was calculated from baseline and standard shoe condition measurements.

2.5. Statistical methods

Data were described as mean and standard deviation (SD). Normal distribution was verified (Kolmogorov-Smirnov-test). A Student's *t*-test was used to verify differences in demographic data between age-groups (Table 1). To analyse systematic effects, a two-way ANOVA with repeated measures (shoe conditions) and a between group effect (women's age) was conducted followed by a post-hoc procedure for the factor shoe conditions (Bonferroni-Test: BASE – CON – HEEL). In case of a significant Mauchly-test, the Greenhouse-Geisser corrected significance level was chosen. Significance was accepted for $p \leq 0.05$. Additionally, Cohen's *d* was calculated for the difference between the

Table 1

Sample characteristics (mean $\pm$ SD) for younger (18–25 years: ≤ 25 n = 19) and middle-aged (26–56 years: > 25 n = 18) women with mean differences and significance level (Student's *t*-test), and for the total sample (n = 37) with minimum and maximum (range) values.

	age (y)	height (m)	weight (kg)	BMI (kg/m ²)	CR10 (points)	heels (cm)	experience (y)	use/week (h)
younger	21.7 (2.6)	1.67 (0.06)	58.1 (7.7)	20.9 (2.0)	0.1 (0.3)	8.6 (1.4)	6.6 (2.9)	5.7 (3.2)
middle-aged	34.1 (8.3)	1.66 (0.07)	59.6 (8.1)	21.6 (2.5)	0.1 (0.3)	8.8 (1.4)	13.5 (5.3)	22.5 (17.4)
mean diff. (p-value)	12.4 (< 0.001)	0.01 (0.766)	1.5 (0.566)	0.7 (0.327)	0.0 (0.622)	0.2 (0.668)	6.9 (< 0.001)	16.8 (0.001)
Total	27.7 (8.7)	1.66 (0.06)	58.8 (7.8)	21.2 (2.3)	0.1 (0.3)	8.7 (1.4)	9.9 (5.5)	13.9 (14.8)
range	(18–56)	(1.54–1.78)	(45–80)	(16.5–27.4)	(0–1)	(7–11)	(3–25)	(2–50)

BMI: Body Mass Index; CR10: category (C) pain scale with ratio (R) properties (Borg, 1990).

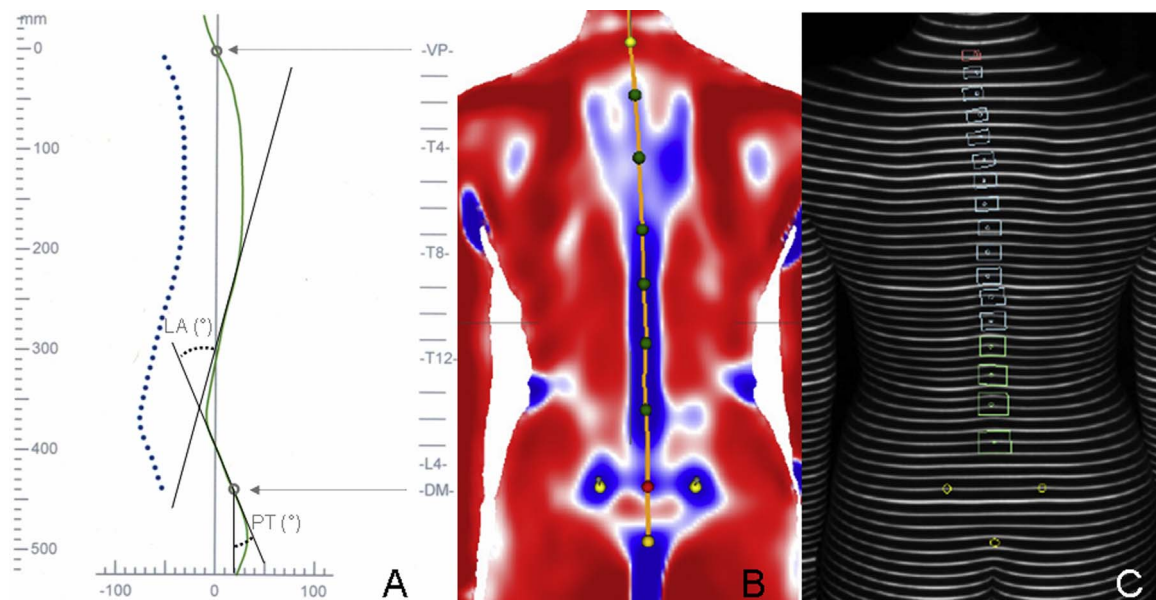


Fig. 1. Lumbar lordosis calculation (A), back shape reconstruction with animation of spinal alignment (spinal processes, the vertebra prominens, the sacrum point, and the lumbar dimples) (B), and raster projection lines ‘in vivo’ with animated dimples, sacrum point and vertebral bodies from C7 to L4 (C) (modified from software DICAM II screen shots). Legend: Lordosis angle (LA°) was calculated from the triangle determined by tangential lines on the back surface at the inflectional point from thoracic kyphosis to lumbar lordosis and the inflectional point from lumbar lordosis to sacral kyphosis. Pelvic tilt (PT°) was determined as the angle between the tangential line on the back surface at the midpoint between dimples (DM) and the plumb line.

control (CON) and high-heeled (HEEL) shoe conditions: $d = 0.20$ indicated a small effect size, $d = 0.50$ a medium effect size and $d = 0.80$ a large effect size, respectively. All statistical calculations were performed with SPSS (Version 20, IBM, Armonk, NY, USA).

3. Results

Outcomes were normally distributed in all dependent variables ($p > 0.10$). Age sub-samples differed significantly in high-heeled shod walking years ($p < 0.001$) and use per week ($p = 0.001$) (Table 1). Reliability of the parameters resulting from the dynamic assessment could be demonstrated as ICCs ranging from 0.826 (LA_ROM°), and 0.915 (P_ROT°) to 0.992 (MLA°).

Under static conditions, the pelvic tilt (PT°) showed a significant shoe effect ($p = 0.003$), but no effect for age ($p = 0.564$) or an interaction ($p = 0.191$). The post hoc procedure revealed a statistically significant decrease for the high-heeled compared to the standard shoe condition ($p = 0.011$, $d = 0.24$) (Table 2).

There was no shoe ($p = 0.619$), no age ($p = 0.970$), and no interaction effect ($p = 0.576$) for the lumbar lordosis angle under static conditions (LA°). Standard control and high-heel shod condition values did not differ ($p = 1.000$, $d = 0.06$) (Table 2).

For dynamic conditions, the pelvic rotation (P_ROT°) revealed a significant shoe effect ($p < 0.001$), showing a greater range of motion for the transversal plane pelvic rotation for high-heels compared to the control condition ($p = 0.004$, $d = 0.63$) (Table 2).

Similar to the static assessment, there were no effects for the lordosis angle under dynamic conditions (MLA°): shoe ($p = 0.181$), age ($p = 0.459$), and interaction effect ($p = 0.613$). The standard control and high-heel shod condition values did not differ ($p = 0.564$, $d = 0.06$) (Table 2).

For the sagittal plane lumbar lordosis range of motion (LA_ROM°) differences were also minimal between standard control and high heel shod condition ($p = 1.000$, $d = 0.03$), showing no significant effects: shoe condition ($p = 0.739$), age ($p = 0.137$), and interaction ($p = 0.544$) (Table 2).

4. Discussion

The purpose of this study was to investigate the effects of high-heeled footwear on static and dynamic pelvic position and lumbar lordosis in young and middle-aged females with experiences in using high-heeled footwear. Our findings showed a small to moderate effect of high-heeled shoes on static ($d = 0.24$) and dynamic ($d = 0.63$) pelvic positions (sagittal pelvic tilt and axial pelvic rotation) in females habituated to the use of high-heeled footwear. In this study cohort no effects of footwear were found on the static or dynamic lumbar lordosis. Thus, our hypothesis of an increased lumbar lordosis due to high-heels had to be rejected for standing as well as for walking.

In line with earlier studies, the lumbar lordosis in the current study was not affected in our sample of experienced participants in either static or dynamic conditions (static: $p = 1.000$, $d = 0.06$; dynamic: $p = 0.564$, $d = 0.06$) [3,11–13]. Some studies found the lumbar lordosis to be decreased in experienced wearers, rather than increased [4,8,9]. Only one study [7] found experienced wearers to have increased lordosis associated with high-heeled shoes, and that sample was very young – 13 to 20 years of age. Increased lordosis has been reported elsewhere for inexperienced wearers [5,10]. So, age as well as wearing experience seems to be a relevant factor influencing the lumbar lordosis. In any case, in our study there was no significant age effect – younger vs. older than 25 years – in any conducted analysis.

Despite no effects of high-heeled footwear on lumbar lordosis, the present investigation revealed some differences in pelvic kinematics. A systematic posterior pelvic tilt was found for both younger and middle-aged women ($p = 0.011$, $d = 0.24$) under static conditions, in line with other investigations [4,7–9]. During walking, an increased pelvic rotation in the transverse plane was observed, which was not dependent on age ($p = 0.004$, $d = 0.63$). This is contrary to Mika et al. [15] who found an increased sagittal plane pelvic range of motion in younger, experienced women only, while middle-aged women did not show pelvic alterations.

In revisiting the belief that the wearing of high-heeled shoes may cause a “chain reaction” of postural alteration superior to the ankle, for the spinopelvic transition we found that it is the pelvis, rather than the lumbar spine, that is more likely involved in postural compensatory

Table 2

ANOVA effects for shoe conditions (BASE-CON-HEEL), age (younger: ≤ 25 y vs. middle-aged: > 25 y), and interactions (shoe $\times$ age) in women for static and dynamic assessment conditions on pelvis position (PT[†], P_ROT[†]), and lumbar curvature (LA[°], MLA[°], LA_ROM[°]) with effect size for the comparison of the randomized measures with standard control (CON) and high-heeled (HEEL) shoes.

		Mean (SD)		ANOVA factors: F-value (p-value)			post-hoc (Bonferroni)			Cohen's d
		younger	middle-aged	age	age $\times$ shoe	shoe	groupwise	difference	p-value	
PT (°)	BASE	23.2 (3.8)	21.6 (5.5)	0.339 (0.564)	1.694 (0.191)	6.171 (0.003)	BASE-CON	0.3	1.000	0.24
	CON	22.9 (3.4)	22.4 (5.3)				BASE-HEEL	0.8	0.025	
	HEEL	21.8 (4.4)	21.3 (4.9)				CON-HEEL	1.1	0.011	
LA (°)	BASE	43.1 (5.9)	43.0 (9.1)	0.001 (0.970)	0.556 (0.576)	0.483 (0.619)	BASE-CON	0.0	1.000	0.06
	CON	43.4 (6.5)	42.7 (9.1)				BASE-HEEL	0.5	1.000	
	HEEL	42.4 (7.0)	42.8 (9.0)				CON-HEEL	0.4	1.000	
P_ROT (°)	BASE	9.5 (2.7)	9.2 (3.0)	0.804 (0.376)	0.883 (0.384)	9.990 (0.001)	BASE-CON	0.3	1.000	0.63
	CON	9.3 (2.7)	8.9 (2.9)				BASE-HEEL	1.6	0.009	
	HEEL	11.7 (3.2)	10.3 (3.2)				CON-HEEL	1.9	0.004	
MLA (°)	BASE	34.2 (7.7)	32.4 (9.2)	0.560 (0.459)	0.406 (0.613)	1.809 (0.181)	BASE-CON	0.1	1.000	0.06
	CON	34.5 (7.8)	32.1 (8.7)				BASE-HEEL	0.6	0.366	
	HEEL	34.8 (7.5)	32.9 (9.1)				CON-HEEL	0.6	0.564	
LA_ROM (°)	BASE	7.2 (3.0)	6.7 (2.5)	2.313 (0.137)	0.526 (0.544)	0.221 (0.739)	BASE-CON	0.3	0.998	0.03
	CON	8.1 (2.8)	6.6 (2.3)				BASE-HEEL	0.2	1.000	
	HEEL	7.9 (3.3)	6.6 (3.1)				CON-HEEL	0.1	1.000	

PT[†]: pelvic tilt (static); LA[°]: lumbar lordosis angle (static); P_ROT[†]: pelvic rotation transversal plane (dynamic); MLA[°]: median lordosis angle (dynamic); LA_ROM[°]: lordosis angle range of motion (dynamic); BASE: baseline test; CON: standard control shoe; HEEL: high-heeled shoe.

strategies. It does not appear that there are *structural* alignment findings in the lumbopelvic transition that could explain an increased risk for back complaints. But from a *functional* point of view, muscular overuse according to the chronic use of high heeled shoes may be leading to more rigid lumbar tissues and future back complaints, perhaps pronounced with advancing age [14,15,25].

We observed an altered gait pattern under high-heel walking conditions measured as increased pelvic rotation in the transversal plane independent of age or wearing experience. In combination with an observed small but systematic posterior pelvic tilt under static high-heel conditions, this may support reasonable assumptions concerning corresponding altered muscle activation patterns described earlier for the erector spinae in combination with an increased pelvic range of motion in the sagittal plane [15]. But explaining the development of high-heel induced low back pain remains difficult, because the altered gait pattern mentioned above were only observed in younger women. Among middle-aged women comparable findings were not reported, which may emphasise the role of habituation [15].

A recent whole body lateral low-dose x-ray study investigated high-heel induced postural alterations in inexperienced wearers not finding altered spinopelvic parameters, but significantly affected hip, knee and ankle angles [3]. The authors concluded that there were different postural adaptation patterns due to high-heels, which may be responsible for different complaints referring to the neck, the lower back or the knees [3]. Another study investigating low back pain in the time course of pregnancy due to postural changes used video rasterstereography plus additional peak force assessments to calculate back muscle forces and torques, but did not demonstrate the altered posture to be a significant back pain risk factor [17].

Having in mind the assumptions dealing with potentially increased risks for the long-term development of high-heel induced back complaints, probable health benefits should not be overlooked. Prolonged standing may lead to increased back pain, but standing on a declining surface – comparable to the wearing of high-heeled shoes – induces postural changes that can reduce back pain reporting during prolonged standing [25]. Comparable to the high-heel low-dose x-ray study of Weitkunat et al. [3], those observed postural changes referred to hip and ankle angles, and not to the lumbar spine shape [25]. Thus, lumbar lordosis should probably not be considered a main factor in high-heel related health risks.

The current investigation had methodological limitations. Muscle force, neuronal activity, and kinematics describing the lower limbs

were not assessed. As this was the first study investigating effects of high-heeled footwear on the spinopelvic parameters by means of video rasterstereography, instrumentation aspects of accuracy and repeatability shall be explicitly discussed. Reliability coefficients for the sagittal plane were reported as excellent ($ICC > 0.95$) for intratester analyses [24] as well as for intertester analyses [26]. For electromechanical inclinometers – e.g. the spinal mouse used by Russell and collaborators for their study [11] – Mannion, Knecht [27] revealed reliability coefficients being very good, but slightly lower for the lumbar lordosis angle ($ICC: 0.90$ – 0.92) compared to rasterstereography. Standard errors – offering an absolute measure for reproducibility of repeated lordosis measurements – were small for the inclinometer ($SEM: 2.4^{\circ}$ – 2.5°), but smaller for rasterstereography ($SEM < 1.0^{\circ}$) [24,27].

With respect to validity considerations it should be noted that rasterstereography is widely used for clinical as well as for scientific purposes for monitoring spinal shape, e.g. in scoliosis patients or pregnant women [17,18]. Although a recent historical review of back surface reconstruction devices noted external validity deficits for the Formetric system, these critical comments referred only to the correlation models for the calculation of vertebral body rotations and not to sagittal plane parameters [28]. Consequently, another systematic review of 2015 concluded that video rasterstereography may be assumed to be valid for screening as well as for monitoring purposes [29]. Comparable systematic reviews attesting validity for the dynamic application of spine shape analysis during gait are lacking so far, but recent investigations demonstrated validity of the Formetric system referring to the gold standard of 3D-Vicon kinematics [19,20].

Heel height at the present study was at least equal or higher compared to earlier studies [4–6,9,10,12,15]. We know that footwear influences biomechanics manifoldly [30]. Nonetheless, the footwear in the present study was not standardized, because of suspected confounding effects due to discomfort and unfamiliarity. The own shoes should provide individual comfort, if the shoes worn in all day activities complied with basic recommendations like heel height.

This cross-over study intended to investigate effects of high-heeled footwear on the lumbopelvic transition among experienced wearers. The repeated measurement design was chosen to control probable individuals' characteristics, e.g. differing spinal curvature with potentially differing adaptation patterns using high-heels. But of course this advantage may bear a limitation, too. The lack of an additional inexperienced control group hampers a generalization of the results.

Thus, possible effects on inexperienced wearers were not part of our investigation. This could be the task of further prospective research.

5. Conclusions

In women, habituated to high-heeled footwear, a primary compensation mechanism during the use of high-heels seems to be pelvis position and movement adaptations rather than lumbar lordosis shape adaptations. The impact of these findings on back complaints should be revisited carefully, because muscular overuse as well as postural load relieving may contribute to complain reporting. Negative as well as positive effects on back pain due to heel elevation are conceivable. Further research would be needed to investigate a probable long-term overuse corresponding to postural alterations.

Conflict of interest

The authors declare no conflict of interests.

Acknowledgement

The authors did not receive financial support for this study.

References

- [1] B.S. Russell, The effect of high-heeled shoes on lumbar lordosis: a narrative review and discussion of the disconnect between internet content and peer-reviewed literature, *J. Chiropr. Med.* 9 (2010) 166–173.
- [2] M.S. Barnish, J. Barnish, High-heeled shoes and musculoskeletal injuries: a narrative systematic review, *BMJ Open* 6 (2016) e010053.
- [3] T. Weitkunat, F.M. Buck, T. Jentsch, H.P. Simmen, C.M. Werner, G. Osterhoff, Influence of high-heeled shoes on the sagittal balance of the spine and the whole body, *Eur. Spine J.* 25 (2016) 3658–3665.
- [4] T. Bendix, S.S. Sorensen, K. Klausen, Lumbar curve, trunk muscles, and line of gravity with different heel heights, *Spine (Phila Pa 1976)* 9 (1984) 223–227.
- [5] M. Dai, X. Li, X. Zhou, Y. Hu, Q. Luo, S. Zhou, High-heeled-related alterations in the static sagittal profile of the spino-pelvic structure in young women, *Eur. Spine J.* 24 (2015) 1274–1281.
- [6] B.J. de Lateur, R.M. Giacon, K. Questad, M. Ko, J.F. Lehmann, Footwear and posture, compensatory strategies for heel height, *Am. J. Phys. Med. Rehabil.* 70 (1991) 246–254.
- [7] P.A. de Oliveira Pezzan, S.M. Joao, A.P. Ribeiro, E.F. Manfio, Postural assessment of lumbar lordosis and pelvic alignment angles in adolescent users and nonusers of high-heeled shoes, *J. Manip. Physiol. Ther.* 34 (2011) 614–621.
- [8] M.E. Franklin, T.C. Chenier, L. Brauninger, H. Cook, S. Harris, Effect of positive heel inclination on posture, *J. Orthop. Sports Phys. Ther.* 21 (1995) 94–99.
- [9] K.A. Opila, S.S. Wagner, S. Schiowitz, J. Chen, Postural alignment in barefoot and high-heeled stance, *Spine (Phila Pa 1976)* 13 (1988) 542–547.
- [10] K.A. Opila-Correia, Kinematics of high-heeled gait with consideration for age and experience of wearers, *Arch. Phys. Med. Rehabil.* 71 (1990) 905–909.
- [11] B.S. Russell, K.A. Muhlenkamp, K.T. Hoiriis, C.M. Desimone, Measurement of lumbar lordosis in static standing posture with and without high-heeled shoes, *J. Chiropr. Med.* 11 (2012) 145–153.
- [12] R.E. Snow, K.R. Williams, High heeled shoes: their effect on center of mass position, posture, three-dimensional kinematics, rearfoot motion, and ground reaction forces, *Arch. Phys. Med. Rehabil.* 75 (1994) 568–576.
- [13] E.E. Cowley, T.L. Chevalier, N. Chockalingam, The effect of heel height on gait and posture: a review of the literature, *J. Am. Podiatr. Med. Assoc.* 99 (2009) 512–518.
- [14] N.J. Cronin, The effects of high heeled shoes on female gait: a review, *J. Electromyogr. Kinesiol.* 24 (2014) 258–263.
- [15] A. Mika, L. Oleksy, P. Mika, A. Marchewka, B.C. Clark, The effect of walking in high- and low-heeled shoes on erector spinae activity and pelvis kinematics during gait, *Am. J. Phys. Med. Rehabil.* 91 (2012) 425–434.
- [16] P. Knott, E. Pappo, M. Cameron, J. Demauroy, C. Rivard, T. Kotwicki, et al., SOSORT 2012 consensus paper: reducing x-ray exposure in pediatric patients with scoliosis, *Scoliosis* 9 (2014) 4.
- [17] G. Schroder, G. Kundt, M. Otte, D. Wendig, H.C. Schober, Impact of pregnancy on back pain and body posture in women, *J. Phys. Ther. Sci.* 28 (2016) 1199–1207.
- [18] J.M. Frerich, K. Hertzler, P. Knott, S. Mardjetko, Comparison of radiographic and surface topography measurements in adolescents with idiopathic scoliosis, *Open Orthop. J.* 6 (2012) 261–265.
- [19] M. Betsch, M. Wild, B. Johnstone, P. Jungbluth, M. Hakimi, B. Kuhlmann, et al., Evaluation of a novel spine and surface topography system for dynamic spinal curvature analysis during gait, *PLoS One* 8 (2013) e70581.
- [20] M. Betsch, M. Wild, P. Jungbluth, M. Hakimi, J. Windolf, B. Haex, et al., Reliability and validity of 4D rasterstereography under dynamic conditions, *Comput. Biol. Med.* 41 (2011) 308–312.
- [21] J. Schroeder, H. Schaar, K. Mattes, Spinal alignment in low back pain patients and age-related side effects: a multivariate cross-sectional analysis of video rasterstereography back shape reconstruction data, *Eur. Spine J.* 22 (2013) 1979–1985.
- [22] G. Borg, Psychophysical scaling with applications in physical work and the perception of exertion, *Scand. J. Work Environ. Health* 16 (Suppl. 1) (1990) 55–58.
- [23] B. Drerup, E. Hierholzer, Back shape measurement using video rasterstereography and three-dimensional reconstruction of spinal shape, *Clin. Biomech.* 9 (1994) 28–36.
- [24] J. Schroeder, R. Reer, K.M. Braumann, Video raster stereography back shape reconstruction: a reliability study for sagittal, frontal, and transversal plane parameters, *Eur. Spine J.* 24 (2015) 262–269.
- [25] K.M. Gallagher, J.P. Callaghan, Standing on a declining surface reduces transient prolonged standing induced low back pain development, *Appl. Ergon.* 56 (2016) 76–83.
- [26] M. Mohokum, S. Mendoza, W. Udo, H. Sitter, J.R. Paletta, A. Skwara, Reproducibility of rasterstereography for kyphotic and lordotic angles, trunk length, and trunk inclination: a reliability study, *Spine (Phila Pa 1976)* 35 (2010) 1353–1358.
- [27] A.F. Mannion, K. Knecht, G. Balaban, J. Dvorak, D. Grob, A new skin-surface device for measuring the curvature and global and segmental ranges of motion of the spine: reliability of measurements and comparison with data reviewed from the literature, *Eur. Spine J.* 13 (2004) 122–136.
- [28] X.C. Liu, J.G. Thometz, J.C. Tassone, L.C. Paulsen, L. RM, Historical review and experience with the use of surface topographic systems in children with idiopathic scoliosis, *OA Musculoskelet. Med.* 1 (2013) 1–8.
- [29] M. Mohokum, S. Schulein, A. Skwara, The validity of rasterstereography: a systematic review, *Orthop. Rev. (Pavia)* 7 (2015) 5899.
- [30] K. Hollander, D. Riebe, S. Campe, K.M. Braumann, A. Zech, Effects of footwear on treadmill running biomechanics in preadolescent children, *Gait Posture* 40 (2014) 381–385.