Influence of High Heeled Footwear and Pre-fabricated Foot Orthoses on Energy Efficiency in Ambulation

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Background: *Although changes in kinematics and repetitive impact forces produced by high heeled footwear can be minimized by pre-fabricated foot orthoses, their effects on energy efficiency and comfort are less understood. The purpose of this study was to investigate if an increase in high heeled footwear and selected pre-fabricated foot orthoses altered energy consumption and improved comfort.*

Materials and Method: *Ten healthy females (age range 21 – 34 years) who were regular high heel wearers volunteered for the study. Five footwear conditions were randomly assigned: heel height of 15mm (flat), 45mm (low), 70mm (high), high with McConnell® orthosis and high with Insolia® orthosis. Heart rate (HR), volume of oxygen consumed in liters per kilogram (VO_2/kg), respiration exchange ratio (RER), physiological cost index (PCI) and the number of steps (NoS) were monitored whilst walking on a treadmill at a speed of 4.2km/hour and 0% incline for 10 minutes. The Footwear Comfort Scale was also completed following each condition.*

Results: *HR, VO_2/kg, RER, PCI and NoS were significantly increased for the high ($p<0.001$) condition compared to the flat and low conditions. Significant differences ($p<0.001$) were also noted between the high and high with McConnell® and Insolia® conditions with a reduced HR, VO_2/kg, RER, NoS and PCI. A significantly improved overall Footwear Comfort Scale was also noted between the high, McConnell® and Insolia® conditions ($p<0.001$).*

Conclusions: *This study supports previous work that wearing high heels are less energy efficient than flat shoes. It also suggests that selected pre-fabricated foot orthoses in high heeled footwear may improve energy efficiency and perceived comfort to wearing high heels alone. These combined benefits and the specific design of biomechanical interventions of orthoses for high heeled footwear should be explored further.*

Key words: High heeled footwear, Energy, Physiological cost index, Pre-fabricated orthosis, Comfort.

Modern day fashion trends continue to promote the design and popularity of high heeled footwear. Surveys have shown that up to 59% of American women[1] and 78% of British women[2] wear high heels on a daily basis.

The reasons for wearing this style of footwear vary greatly with many women stating that they feel more confident and glamorous from the extra height gained.[1,3] A further attraction relates to the appearance of a shorter foot, which is achieved by increasing arch height.[4,5] This is also supported by Frey et, al.,[6] who found that 86% of American women wore high heeled footwear that was too small for their feet.

Whilst elegance is perceived as a key characteristic, by its very nature the design of high heeled footwear can be considered as having a profound impact on gait and posture, and in particular lower limb function.

Efficient walking is achieved by forward transmission of one limb to the next using the least amount of energy.[7] Footwear with a low heel is thought to conserve energy by providing a normal heel strike and smooth forward transmission of the limb. In contrast, high heeled footwear can result in an early heel strike and increased rearfoot inversion.[8-11] Other alterations are a plantarflexed ankle throughout stance, which produces postural changes causing the hip and knee to flex.[9,12-14] The plantarflexed foot position increases loading to the forefoot and in particular the first and second metatarsal heads.[8,15-21] During swing phase, hip flexion is thought to be reduced, and whilst cadence may not be affected by high heels, stride length and velocity are decreased.[12] Muscle function is also altered during high heeled walking[8,22-26] with constant contraction of the lateral head of the gastrocnemius[25] and an increase in activity of tibialis anterior[23,26] and rectus femoris.[26]

As a consequence to these changes, high heeled footwear is frequently linked as a cause or aggravating factor of pain and symptoms in the lower back, hip, knee, ankle and foot.[15,27,28] In particular, evidence suggests that individuals who wear a high heel take a longer period of time to reach maximum knee flexion which disrupting the screw home mechanism of the knee and thus predisposes the joint to injury. Moreover, Stefenyshyn, et al.,[29] showed that compared to barefoot, high heeled footwear increased concentric knee extensor activity. These findings are also supported by Kerrigan, et al.,[30-32] who found that high heels increase peak varus torque by up to 26% when compared to barefoot. As a result, these factors are thought to produce abnormal forces at the tibiofemoral and patellofemoral joint which in turn predisposes the knee to injury and degeneration.

Foot orthoses are considered to be beneficial in reducing the repetitive impacts and changes in kinematics produced by high heeled footwear. In particular, they aim to improve weight distribution, comfort and stability. A previous study by Yung-Hui and Wei-Hsien[15] showed that custom made foot orthoses can reduce impact forces; heel and medial forefoot pressures, and improve perceived comfort compared to no insert. In particular, the total contact insole (TCI) showed the largest reduction in impact force (33.2%) and medial forefoot pressure (24%), and the highest perceived comfort compared to no insert. This study addressed kinetics and comfort of custom made orthoses. The contributions of alterations to energy consumption and perceived comfort to an increased heel height have not been investigated using pre-fabricated foot orthoses.

Whilst it is clear that a number of studies have explored the effects of high heeled footwear on lower limb function and loading, only a few have reported their effects on energy consumption. Mathews and Wooten[33] noted an increase in energy expenditure in 10 females who walked on a treadmill wearing high heeled footwear. Ebbeling, et al.,[28] also showed an increase in expenditure in heel heights of 50.8mm and above.

Energy consumption or expenditure is commonly recorded by directly measuring the volume of oxygen an individual has consumed. This approach however, is frequently restricted to a laboratory setting and has led to the introduction of proxy measures such as the *'physiological cost index'*. (PCI)[34] This simple measure determines walking efficiency[35] which has proven to be valid and reliable in a variety of health disciplines.[36] It is also able to discriminate between various treatment interventions and walking devices.[37-39] Nonetheless, to date the ability of the PCI to respond to changes in heel height is currently unknown and therefore requires investigation.

Investigating the impact of high heeled footwear and the effects of foot orthoses on energy consumption and comfort can provide the basis for improving the design of an orthosis and how to minimize pain and discomfort. The aim of this study was to examine if an increase in high heeled footwear and selected pre-fabricated foot orthoses changed energy consumption and improved perceived comfort. A secondary aim was to determine if the PCI, a proxy measure of energy consumption could be used as an indicator for monitoring the amount of energy used when wearing high heeled footwear.

Methods

Participants and materials

Ten female university students volunteered to take part in the study. The participants had a mean age of 26.3 years (standard deviation [SD] 5.4, range 21 – 34 years), mean weight of 61.4kg (SD 7.9, range 51 – 73.9kg), and mean height of 160.5cm (SD 4.4, 153 – 167cm). All participants met the following inclusion criteria: no cardiovascular or neuromusculoskeletal conditions that might influence their walking pattern; currently wear footwear (size 5 [38] – 6 [39]) with a heel 2 – 5 times a week for at least 1 year. Ethical approval was sought from the School of Health Sciences Ethics Committee, University of Wales Institute, Cardiff before the study began. The study's purpose and procedures was fully explained to each participant. Informed consent was obtained from all participants before taking part.

The footwear used in this study was commercially available (Clarks© Ltd, UK) and were selected based on the similarity of construction such as forefoot width (D fitting) with a strap style and foot contact points. The key difference among this footwear was the height of the heel: a flat (15mm), a low (45mm) and a high heel (70mm) (Fig. 1 A – C). The foot orthoses used were commercially available pre-fabricated products: Insolia® (Insolia®, Salem, New Hampshire, USA) (Fig. 2 A and C) and Vasyli McConnell® Extended slim fit (Vasyli® International, Australia) (Fig. 2 B, D – E). To prevent slippage within the shoe, a new piece of double sided adhesive tape was applied to each prefabricated insert before each trial. Each participant was randomly assigned five conditions: (1) flat only (15mm); (2) medium only (45mm); (3) high only (70mm); (4) McConnell® (with high, 70mm); (5) Insolia® (with high, 70mm).

Equipment

A Woodway (Desmo, Germany) treadmill was used for each of the 5 experimental conditions. Volume of oxygen consumed in litres per kilogram (VO2/kg) and respiration exchange ratio (RER) were collected and calculated at one minute intervals using a Metalyzer 3B-R2 (Cortex, Germany).

The RER is the carbon dioxide (CO2) divided with O2 consumption. Heart rate (HR) was monitored using a VFIT monitor (Polarexpress Ltd, London), which was attached to the participant's chest by a strap. This telemetry system records the electrical signals generated from the heart by the transmitter worn on the chest and displayed on a wristwatch receiver. A pedometer was used to record the number of steps (NoS) taken (WSG™ Digital Pedometer). The sensitivity of the pedometer was determined using the 'shake test' as described by Vincent and Sidman40 before data collection began. The pedometer was found to be within 3% of the actual number of shakes. The pedometer was positioned according to manufacturer's instructions, and before data began the step number was cleared.

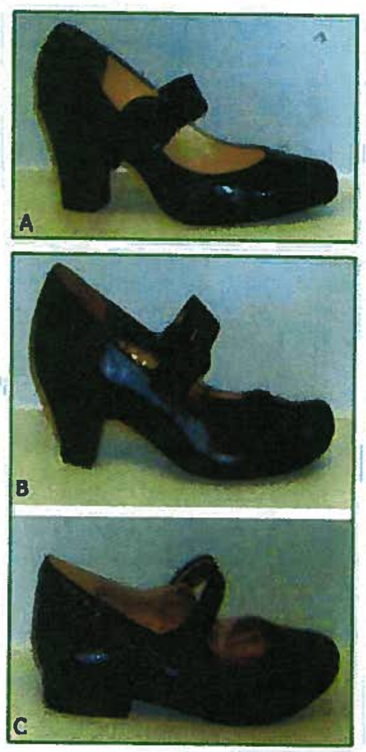

Figure 1 Footwear used for study (Clarkes© Ltd, UK). (A = high, B = medium, C = flat)

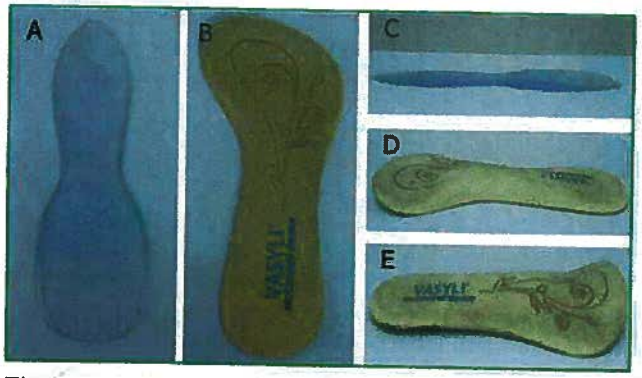

Figure 2 Pre-fabricated orthotic inserts. A) and C) Insolia® – the medial and lateral aspect of the insert are symmetrical. B), D) and E) McConnell® – an increased in height of medial aspect of the insert is noted (D) compared to the lateral (E).

Footwear Comfort Scale

Following each walking trial the Footwear Comfort Scale[41] was used to determine the perceived comfort for the 5 conditions. The scale has been used by a number of authors[15, 42] and consists of 8 questions (i.e. overall comfort, forefoot cushioning). Perceived comfort is rated using a 15mm visual analogue scale (VAS), with 0 (= 0 comfort point) labeled as *'not comfortable at all'* and 15 as *'the most comfortable condition imaginable'* (= 15 comfort points). For consistency, each participant was advised not to take into account the style and cosmetics of the footwear during comfort rating.

1.	Overall comfort
2.	Heel cushioning
3.	Forefoot cushioning
4.	Medio-lateral control
5.	Arch height
6.	Heel cup
7.	Heel width
8.	Shoe length

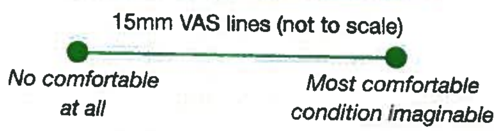

Figure 3 Eight questions of the Footwear Comfort Scale and the 15mm VAS line.

Procedures

Data was collected in a quiet physiology laboratory over 2 sessions, at the same time of day for approximately 1 hour. Prior to testing, the order for each experimental condition was randomly assigned to the participant to eliminate order effects. Before data collection began, each participant was given a 5 minute acclimatization period on the treadmill for each experimental condition. The speed of walking was standardized to 4.2km/hour at a 0% incline. This speed was chosen because it falls within the mean comfortable speed.[8,11,15,43]

Following acclimatization, data were collected over a further 5 minutes at the same standardized speed. To minimize fatigue, each participant was allowed a 20 minute rest between each experimental condition and/or until their HR returned to its resting value. Each participant was instructed to look straight ahead whilst walking on the treadmill. The procedure was terminated if the participant felt uncomfortable, showed an unsteady gait, signaled to stop or when the walking period was completed.

Data and statistical analysis

The mean, SD and range were calculated for all of the measures investigated. The PCI was calculated using the following equation: Walking heart rate – resting heart rate divided by speed (m/min).[34] A series of Kolmogorov-Smirnov tests were performed and showed all data to have a normal distribution $p<0.001$. A one-way analysis of variance (ANOVA) was performed to investigate the differences between each of the five conditions, whilst Tukey's post hoc analysis was used to identify where the differences occurred. All data were analyzed using the software package SPSS® (version 15.0, London, UK) and a significance level set a $p<0.05$.

Measure	Flat	Medium	High	McConnell®	Insolia®
HR* (beats/min)	85 ± 2.4 (60 – 111)	95.4 ± 3.2 (65 – 124)	111.1 ± 4.0 (98 - 130)	96.3 ± 5.9 (76 – 131)	97.8 ± 5.1 (71 – 122)
VO2/kg*	13.2 ± 1.7 (10 – 16)	15.6 ± 2.2 (13 – 19)	19 ± 2.4 (14 – 25)	14.8 ± 2.6 (12 – 18)	14 ± 1.8 (10 – 17)
RER*	0.64 ± 0.07 (0.49 – 0.71)	0.79 ± 0.10 (0.66 – 2.98)	0.85 ± 0.06 (0.76 – 0.98)	0.70 ± 0.04 (0.65 – 0.76)	0.64 ± 0.09 (0.41 – 0.75)
NoS*	1034 ± 35.1 (994 – 1086)	1196.8 ± 46.2 (1140 – 1463)	1257.1 ± 42.5 (1217 – 1334)	1134.7 ± 42.5 (1005 – 1198)	1095.4 ± 44.7 (1021 – 1198)
PCI* (beats/min)	0.175 ± 0.09 (0.01 – 0.33)	0.412 ± 0.20 (0.21 – 0.76)	0.623 ± 0.15 (0.39 – 0.93)	0.37 ± 0.34 (0.2 – 0.49)	0.322 ± 0.11 (0.20 – 0.63)

Table 1 Mean, SD and range of each condition and variable measured (*significant differences $p<0.001$, one-way ANOVA).