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.

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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.

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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

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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 (VO_2/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 (CO_2) divided with O_2 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 Sidman[40] 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)

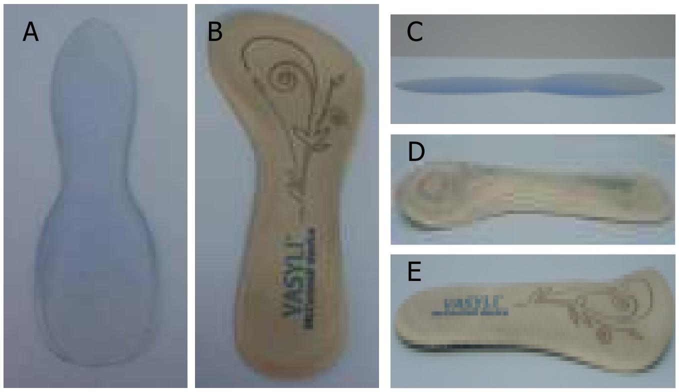

Figure 2 Pre-fabricated orthotic inserts. A) and C) Insolia® – the medial and lateral aspect of the insert are symmetrical. B), D) and E) McConnell® – an increased in height of medial aspect of the insert is noted (D) compared to the lateral (E).

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

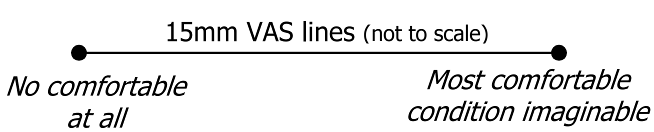

Figure 3 Eight questions of the Footwear Comfort Scale and the 15mm VAS line.

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	95.4 ± 3.2	111.1 ± 4.0	96.3 ± 5.9	97.8 ± 5.1
	(60 – 111)	(65 – 124)	(98 - 130)	(76 – 131)	(71 – 122)
VO_2/kg*	13.2 ± 1.7	15.6 ± 2.2	19 ± 2.4	14.8 ± 2.6	14 ± 1.8
	(10 – 16)	(13 – 19)	(14 – 25)	(12 – 18)	(10 – 17)
RER*	0.64 ± 0.07	0.79 ± 0.10	0.85 ± 0.06	0.70 ± 0.04	0.64 ± 0.09
	(0.49 – 0.71)	(0.66 – 2.98)	(0.76 – 0.98)	(0.65 – 0.76)	(0.41 – 0.75)
NoS*	1034 ± 35.1	1196.8 ± 46.2	1257.1 ± 42.5	1134.7 ± 42.5	1095.4 ± 44.7
	(994 – 1086)	(1140 – 1463)	(1217 – 1334)	(1005 – 1198)	(1021 – 1198)
PCI* **(beats/min)**	0.175 ± 0.09	0.412 ± 0.20	0.623 ± 0.15	0.37 ± 0.34	0.322 ± 0.11
	(0.01 – 0.33)	(0.21 – 0.76)	(0.39 – 0.93)	(0.2 – 0.49)	(0.20 – 0.63)

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

Results

Differences: Metabolic variables and efficiency

The mean, SD and range for HR, VO_2/kg, RER, NoS and PCI for each of the experimental condition are summarized in table 1. The one-way ANOVA showed significant differences between the five conditions for HR ($F = 3.522$, *df* 4, $p=0.014$). RER ($F = 14.418$, *df* 4, $p<0.001$); VO_2/kg ($F = 7.391$, *df* 4, $p<0.001$); NoS ($F = 14.190$, *df* 4, $p<0.001$), and PCI ($F = 12.532$, *df* 4, $p<0.001$).

Tukey's post hoc analysis for HR only revealed significant differences ($p<0.001$) between flat and high condition, with a 23.5% increase in HR noted for the high condition. Post hoc analysis for VO_2/kg demonstrated a series of significance differences ($p<0.001$) between the flat and medium, flat and high conditions. An increase in VO_2/kg of 22.4% was noted for the high condition and slightly lower value of 15.5% observed for the medium condition.

Further differences were demonstrated between the high and McConnell® and Insolia® conditions. The VO_2/kg was reduced by 22.2% for the McConnell® and 26.5% for the Insolia® condition.

Tukey's post hoc comparisons revealed differences between the flat and high condition for the RER with a 25% (0.21) increase noted for the high condition. Significance differences were also noted between the high, the McConnell® and Insolia® conditions. The RER was noted to be reduced by 18% (0.15) and 25% respectively (0.21) compared to the high condition.

Post hoc analysis for the PCI revealed significant differences between the flat and medium, and flat and high conditions. A lower PCI of 58% (0.237) and 72% for the flat condition was noted when compared to the medium and high conditions respectively. Tukey's analysis also demonstrated significant differences between the high and McConnell® and Insolia® conditions ($p<0.001$). The PCI was reduced by 49% and 41% for the McConnell® and Insolia® condition when compared to the high heel conditions.

Post hoc analysis demonstrated significant differences for NoS between all three height conditions (i.e. flat, medium and high) with more steps taken for the medium (13.6%) and high (17.8%) conditions.

Post hoc analysis also showed significant differences between the high and McConnell®, and high and Insolia® conditions. Fewer steps were taken with McConnell® (10.8%) and Insolia® (13.7%) conditions.

Differences: Footwear Comfort Scale

The one-way ANOVA indicated significant differences between the five conditions for overall comfort (F = 4.213, *df* 4, p=0.06), heel cushioning (F = 5.108, *df* 4, p=0.002), forefoot cushioning (F = 5.571, *df* 4, p<0.001) and heel cup fit (F= 8.308, *df* 4, p<0.001). No significant differences were noted between the five conditions for the medio-lateral control (F = 8.470, *df* 4, p=0.269), arch height (F = 1.387, *df* 4, p= 0.254); shoe heel width 7.802, df 4, p=0.063), and shoe length (F = .783, *df* 4, p=0.542). Fig. 3 illustrates the comparison of perceived ratings for the five conditions.

Compared to the high condition (mean 7.8, SD 2.8) tukey's post hoc analysis showed a significantly higher overall comfort rating for the McConnell® (mean 11.8, SD 1.6) and Insolia® conditions (mean 11.1, SD 1.4), with a 34% and 30% increase respectively. Post hoc analysis using Tukey's revealed significant differences between the high and McConnell® (p=0.018) and the medium and McConnell® (p=0.002) conditions for heel cushioning. The mean rating of 12.9 (SD 1.5) was noted for the McConnell® condition, and was increased by 29% (mean 9.2, SD 2.7) and 35% (mean 8.4, SD 3.9) compared to the high and medium conditions.

Post hoc analysis demonstrated significant difference between the flat and high condition (p=0.017) for forefoot cushioning. It was noted that the flat condition had a mean rating of 9.2 (SD 2.8), whilst the high condition had a reduced rating of 6 (SD 1.2) producing a mean difference of 35%.

Further significant differences were noted between the high and McConnell® (p=0.034) and Insolia® (p<0.001) conditions for forefoot cushioning. The McConnell® condition had a higher mean rating of 9.4 (SD 1.5), whilst a rating of 11 (SD 1.2) was noted for the Insolia® condition. Compared to the high condition, this produced a mean difference of 36.5% and 46% for the McConnell® and Insolia® condition respectively.

Post hoc analysis also showed significant differences for heel cup fit between the flat and medium (p<0.001); flat and high (p<0.001); medium and McConnell® (p=0.035); and high and McConnell® (p=0.022) conditions. The flat condition had a higher mean rating of 11.4 (SD 2.5) compared to the medium and high conditions which had ratings of 6.2 (SD 2.9) and 6 (1.2) respectively. This produced a mean difference of 46% for the medium and 47% for the high condition. The McConnell condition had a mean heel cup fit rating of 9.6 (SD 2.2), which was 35.5% and 38% higher compared to the medium and high conditions. Figure 4 illustrates the mean values for each sub-section of the Footwear Comfort Scale and the significant differences between conditions.

Discussion

This study sought to establish the influence of high heeled footwear and pre-fabricated foot orthoses on gait efficiency and perceived comfort. A further aim investigated if a proxy measure, the PCI could be used as an indicator for assessing energy expenditure whilst wearing high heeled footwear. The results of this study demonstrated clear links between an increase in energy and a reduction in perceived comfort as heel height increased. This link was reduced (reversed) upon the implementation of 2 types of pre-fabricated foot orthoses (McConnell® and Insolia®) which showed an improved efficiency and perceived comfort.

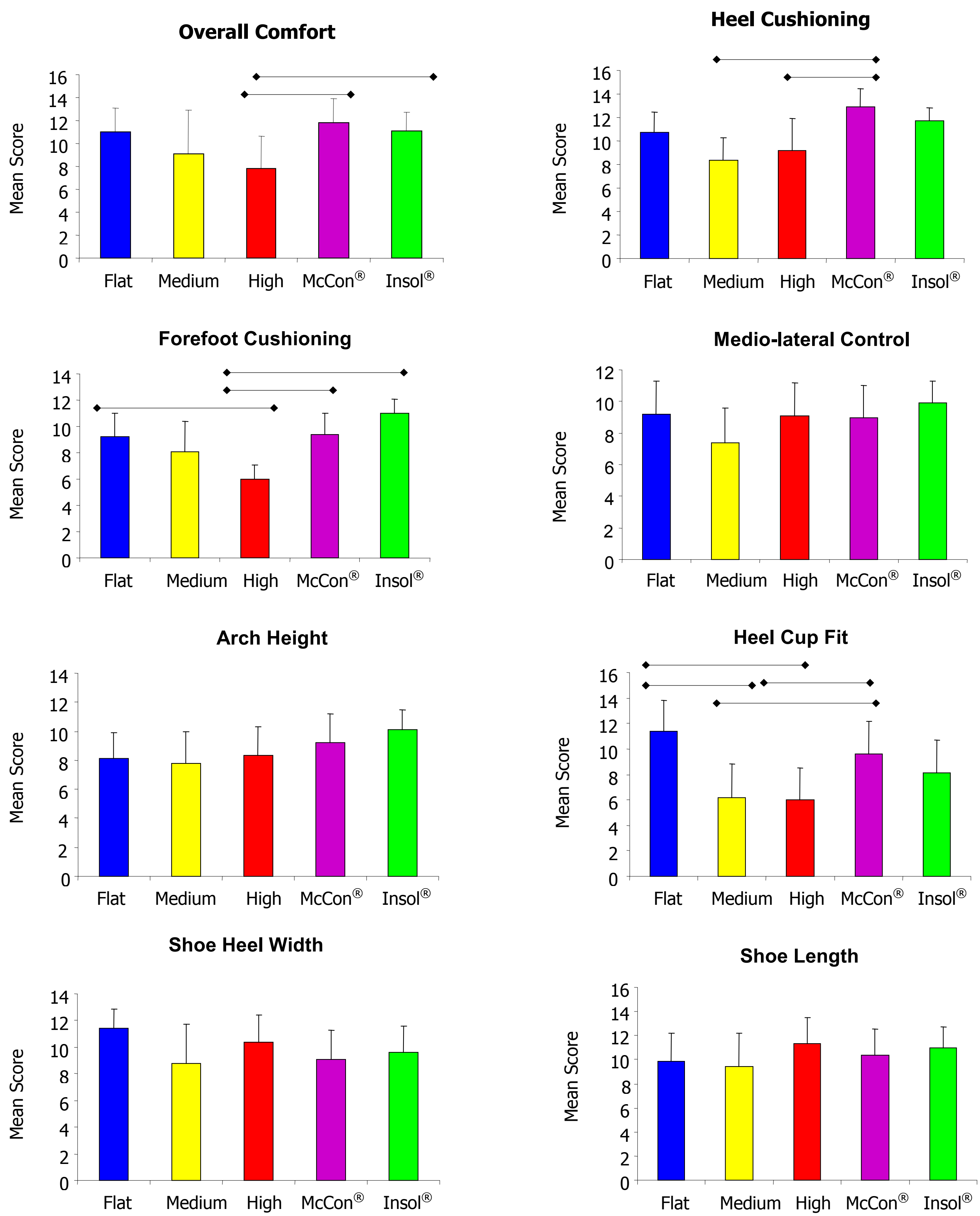

Figure 4 Footwear Comfort Scale results for all five conditions. (◆———◆ = $p<0.05$ significant differences between conditions) (McCon® = McConnell®; Insol® = Insolia®)

In this study, energy efficiency was derived from a series of measures which included HR, RER, VO_2/kg and PCI. Although HR only showed a significantly higher increase of 23.5% for the high condition compared to the low, this finding is consistent with previous studies.[28,43] Significant differences were noted between all five conditions for RER, VO_2/kg and PCI. It was noted that the largest increase occurred between the flat and high conditions for the RER and VO_2/kg, which again supports previous literature.[28]

The data for the RER was at its highest (0.85) for the high condition which suggests that both fat and carbohydrates were the fuel source. Whilst the RER for the medium condition was at 0.79 (approaching a mixed source fuel), it was noted that that the use of the McConnell® and Insolia® orthoses significantly reduced the RER to 0.70 and 0.64. This may indicate that the amount of energy (i.e. fat) used was reduced thus increasing overall efficiency. However, it could be argued that the RER results presented here seem a little high, which could be attributed to a small sample size. Therefore, further research involving a longer period of walking would be useful to gain a clearer picture of this parameter in high heel walking.

The PCI showed similar trends, but most notable were the significant differences observed between the high and McConnell® and Insolia® conditions. Here the values for the PCI were reduced to 49% (McConnell®) and 41% (Insolia®) and whilst these values were not as low as flat condition, the results do suggest that the use of pre-fabricated foot orthoses can reduce the amount of energy consumed. Since no previous data exists for the PCI in relation to high heeled footwear and pre-fabricated foot orthoses, direct comparisons are limited.

It is known that at a set speed, the most economical stride length and NoS are chosen. For this study, a pedometer was used to measure the naturalistic activity of the NoS for each condition whilst walking at a standardized speed of 4.2km/hour.

There was an increase in the NoS taken during the medium (13.6%) and high (17.8%) conditions compared to the flat condition. The increased use of energy whilst walking in high heels can be explained by the changes in lower limb biomechanics and stride pattern. An increase in heel height is considered to plantarflex the foot, and flexes the hip and knee. These angular changes therefore result in a shorter stride length.[8,9,12,15,19,28,44] Since the speed was kept constant throughout all of the conditions, the NoS during the high condition had to increase, which in turn, used more energy. Comparisons between the high and orthoses condition also showed significant differences with fewer NoS taken for the McConnell® (10.8%) and Insolia® (13.7%) conditions. Taking larger and fewer steps however may be a negative factor since less steps may result in higher sagittal and varus knee torques[30-32] which in turn leads to joint damage (i.e. degenerative changes of the tibiofemoral and patellofemoral joints). Moreover, longer activation times of the rectus femoris[16] and co-contraction of other lower limb muscles may also be linked to longer stride patterns which warrants further exploration.

While the findings presented in this study cannot suggest a dramatic angular change within the lower limb, it could be assumed that the pre-fabricated orthoses discreetly altered lower limb function. This assumption relates to a new paradigm advocated by Nigg which suggests that orthoses can filter the impact forces placed upon the foot and adjust muscular response to allow the individual to sustain their '*preferred movement pathway*.'[45] Although it can be stated that wearing high heels will always influence lower limb function, adaptability to the condition and cushioning via foot orthoses are likely to have contributed to these changes. Moreover, all participants who took part in this study were experienced heel wearers and are likely to have already undergone soft tissue adaptation in the form of Davis's law.[46]

Whilst kinetic analysis was beyond the scope of this present study, it could be assumed that the elastic (pressure) and viscosity (impact force) properties of the orthosis material could provide a number of benefits. For example, as well as providing cushioning they may have enhanced the capability of energy absorption and potential kinetic energy the lower limb body already processed. This may be particularly relevant for the McConnell® orthosis during heel impact, since it appeared to provide more cushioning. The Insolia® product however, is devised on the principle that weight is shifted posterior to the rearfoot, minimizing pressure and force within the forefoot. By controlling this pathway of progression during walking it could be suggested that less energy is used and stored, thus creating improved efficiency whilst walking in high heels.

Perceived comfort was influenced by heel height and the use of the orthoses (McConnell® and Insolia®). Four out of the eight sections of the Footwear Comfort Scale (overall comfort, heel cushioning, forefoot cushioning and heel cup fit) were significantly different between the five conditions. The mean overall comfort rating was 11 for the flat condition but reduced to 7.8 for the high heel condition. This value however, improved with the use of the McConnell® (mean 11.8) and Insolia® (mean 11.0) orthoses. These findings support previous work [3,15] and suggest that higher heels are uncomfortable, but the use of pre-fabricated foot orthoses can provide an improved comfort which is similar to that of flat footwear. Whilst the McConnell® and Insolia® conditions showed significantly improved ratings compared to the high condition (mean 9.2) for heel cushioning, it was noted that the McConnell® orthosis had a higher comfort score. This however, was not significant, but may indicate better shock absorbing properties of the McConnell® orthosis.

As with previous subsections of the footwear scale, the mean forefoot comfort score for the flat foot was higher at 9.2 and reduced to 6 for the high condition. This was the lowest comfort score out of the 8 conditions; however the use of pre-fabricated foot orthoses significantly improved comfort with a mean of 11.7 noted for the McConnell® and 12.9 for the Insolia® orthosis. The lower value noted for the McConnell® orthosis can be attributed to impingement under the first metatarsal head that was stated by 7 out of the 10 participants. Furthermore, the improved comfort experienced during the Insolia® condition could be due to the reduced pressures at the forefoot as the orthosis shifts the weight from the forefoot to the midfoot and rearfoot.

A number of limitations are acknowledged in this study. Firstly, the study may have been limited to the immediate effects of orthoses and the various heel heights on gait efficiency and perceived comfort. Secondly, the sample size was small and did not include a wide age range. Thirdly, data collection was limited to a laboratory setting and required participants to walk at a standardized speed in a straight line over a short period of time.

This approach can be considered as unrealistic since it fails to capture the everyday setting such as the required multi-directional changes in walking pattern and fatigue often experienced by women at the end of a day. In spite of these limitations, the inclusion of the PCI in this study has shown that it responds to an increase in heel height. The measure is appealing, since it is a simple and cost effective tool that can be used outside of the laboratory. Future research should focus on a larger and more diverse sample population that should include data collection at the beginning and end of the day to establish the role of fatigue. Multi-directional walking patterns such as the *'figure of 8'* method[36] could also be used. Information gained from additional studies can help to document the effects of high heeled footwear and to optimize the design and selection of pre-fabricated orthoses.

Clinical significance

The findings of this study should be viewed in terms of clinical context and significance. The wearing of high heeled footwear is discouraged by health care professionals with an interest in lower limb function and care. However, products such as the McConnell® and Insolia® (as well as others) have been produced in an attempt aid comfort and reduce the damaging impacts associated with wearing high heels. Whilst this study suggests some benefits of pre-fabricated foot orthoses when wearing high heels, further research is required. This should involve kinetic, kinematic and electromyography to determine the effects of these pre-fabricated orthoses over a set period of time (i.e. to establish fatigue patterns).

Conclusion

The present results provide further information of the influence of high heeled footwear on energy efficiency and perceived comfort. The use of 2 pre-fabricated orthoses; the McConnell® and Insolia® have been shown to reduce the amount of energy used, as well as improve comfort whilst wearing footwear with a 75mm heel. The PCI represents a useful measure for documenting walking efficiency in high heeled footwear. Future research should be undertaken to determine how well the results generalize to more realistic walking patterns (multi-directional) and longer periods of wear to establish fatigue.

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Conflicts of Interest

There are no conflicts of interest.

References

1. The Gallup Organization Inc. Women's attitudes and usage of high heel shoes. The Gallup Organization Inc. Surrey, England (August), 1986.
2. The Ogilvy Group. British women's daily battle with high heels. 2007 July. http://www.feetforlife.org/cgi-bin/item.cgi?id=1850&d=pnd&h=0&f=0&dateformat=%25o%20%25B%20%25Y Accessed 25th October 2009.
3. Au EY, Goonetilleke RS. A qualitative study on the comfort and fit of ladies' dress shoes. Appl Ergonomics 2007; 38 (6): 687- 696.
4. Ricci B, Karpovich PV. Effect of height of heel upon the foot. Res Q 1964 35: 385-388.
5. Schwartz P, Heath WL. Preliminary findings from roentgenographic study of the influence of heel height and empirical shank curvature on osteo-articular relationships in the normal female foot. JBJS 1959 41A: 1065-1076.
6. Frey C, Thompson F, Smith J, Sanders M, Horstman H. American Orthopaedic Society women's shoe survey. Foot Ankle 1993 14(2): 78-81.
7. Waters RL, Mulroy S. The energy expenditure of normal and pathological gait. Gait Posture 1999 9: 207-231.
8. Esenyel M, Walsh K, Walden JG, Gitter A. Kinetics of high-heeled gait. JAPMA 2003 93 (1): 27-33.
9. Lee CM, EH Jeong, Freivalds A: Biomechanical effects of wearing high-heeled shoes. Int J Industrial Ergo 2001 28: 321-326.
10. Whittle MW. Generation and attenuation of transient impulsive forces beneath the foot: a review. Gait Posture 1999 10 (3): 264-275.
11. Snow RE, Williams KR. High heeled shoes: their effects on center of mass position, posture, three dimensional kinematics, rearfoot motion, and ground reaction forces. Arch of Phys Med Rehabil 1994 75 (5): 568-576.
12. Opila-Correia KA. Kinematics of high heeled gait. Arch Phys Med Rehabil 1990 71: 905-909.
13. Murray MP, Kory RC, Sepic SB. Walking patterns of normal women. Arch of Phys Med Rehabil 1970 51: 637-650.
14. Gollnick PG, Tipton CM, Karpovich PV. Electrogoniometric study if walking in high heels. Res Q Exer Sport 1964 35: 370-378.
15. Yung-Hui L. Effects of shoe inserts and heel height on foot pressure, impact force, and perceived comfort during walking. Appl Ergonomics 2005 36: 335-362.
16. Hwang YT, Pascoe DD, Kim CK, Xu D. Force patterns of heel strike and toe off on different heel heights in normal walking. Foot Ankle Int 2001 22 (6): 486-492.

17. Mandato MG, Nester E: The effects of increasing heel height on forefoot peak pressure. JAPMA 1999 89 (2): 75-80.
18. Nyska M, MCCabe C, Linge K, Klenerman L. Plantar foot pressures during treadmill walking with high-heel and low-heel shoes. Foot Ankle Int 1996 17(11): 662-666.
19. Eisenhardt JR, Cook D, Pregler I, Foehl HC. Change in temporal characteristics and pressure distribution for barefeet versus various heel heights. Gait Posture 1996 4 (4): 280-286.
20. Corrigan JP, Moore DP, Stephens MM. Effect of heel height on forefoot loading. Foot Ankle 1993 14 (3): 148-152.
21. McBride ID, Wyss UP, Cooke TD, Murphy L, Phillips J, Olney SJ. First metatarsophalangeal joint reaction forces during high-heel gait. Foot Ankle 1991 11 (5): 282-288.
22. Edwards L, Dixon J, Kent JR, Hodgson D, Whittaker VJ. Effect of shoe heel height on vastus medialis and vastus lateralis electromyographic activity during sit to stand. J Orthopaedic Surgery Research 2008 3: (2).
23. Joseph J. The pattern of activity of some muscles in women walking on high heels. Ann Phys Med 1968 9 (7): 295-299.
24. Joseph J, Nightingale A. Electromyography of muscles of posture: Leg and thigh muscles in women, including the effects of high heels. J Physiol 1956 132: 465-468.
25. Basmajian JV, Bentzon JW: An electromyographic study of certain muscles of the leg and foot in the standing position. Surg Gynecol Obstetrics 1954 98: 662-666.
26. Hwang SJ, Choi HS, Choi HH, Kim HS, Kim YH. The evaluation of the lower extremity joint moments and muscle force during various high-heel walking. Key Engineering Mat 2006 26 - 328: 755-758.
27. Zipfel B, Berger LR. Shod versus unshod: The emergence of forefoot pathology in modern humans? The Foot 2007 17: 205-213.
28. Ebbeling CJ, Hamill J, Crussemeyer JA. Lower extremity mechanics and energy cost of walking in high-heeled shoes. JOSPT 1994 19 (4): 190-196.
29. Stefanyshyn D, Nigg BM, Fisher V, O'Flynn B, Liu W. The influence of high heeled shoes on kinematics, kinetics, and muscle EMG of normal female gait. J Appl Biomech 2000 16: 309-319.
30. Kerrigan DC, Johansson J, Bryant M, Boxer J, Della Croce U, Riley P: Moderate-heeled shoes and knee joint torques relevant to the development of the progression of knee osteoarthritis. Arch Phys Med Rehabil 2005 86 (5): 871-875.
31. Kerrigan DC, Lelas JL, Karvosky ME: Women's shoes and knee osteoarthritis. Lancet 2001 357 (9262): 1097-1098.
32. Kerrigan DC, Todd MK, Riley PO: Knee osteoarthritis and high heeled shoes. The Lancet 351 (9): 1399 – 1401, 1998.
33. Mathews DK, Wooten EP: Analysis of oxygen consumption of women while walking in different style shoes. Arch of Phys Med Rehabil 1963 44: 569-571.
34. Macgregor J. Rehabilitation ambulatory monitoring. In Kendi R, Paul J, Hughes J (eds). Disability. London: Macmillan, 159 – 172, 1979.
35. Sienko Thomas S, Buckon CE, Schwartz MH, Sussman MD, Aiona MD. Walking energy expenditure in able-bodied individuals: a comparison of common measures in energy efficiency. Gait Posture 2009 29 (4): 592-596.
36. Graham RC, Smith NM, White CM. The reliability and validity of the physiological cost index in healthy subjects while walking on 2 different tracks. Arch Phys Med Rehabil 2005 86: 2041-2046.
37. Hood VL, Granat MH, Maxwell DJ, Hasler JP. A new method of using heart rate to represent energy expenditure: the total Heart Beat Index. Arch Phys Med Rehabil 2002 83: 1266-1273.
38. Burridge JH, McLellan DL. Relation between abnormal patterns of muscle activation and response to common peroneal nerve stimulation in hemiplegia. J Neuro Neurosurg Psychiatry 2000 69: 353-361.
39. Steven MM, Capell HA, Sturock RD, Macgregor J. The physiological cost of gait (PCG): a new technique for evaluating non-steroidal anti-inflammatory drugs in rheumatoid arthritis. Brit J Rheum 1983 22: 141-145.
40. Vincent S, Sidman C: Determining measurement error in digital pedometers. Measurement Phys Education Exercise 2003 7: 19-24.
41. Mundermann B, Nigg BM, Stefanbyshyn D, Humble R. Development of a reliable method to assess footwear comfort during running. Gait Posture 2002 16: 38-45.
42. Eslami M, Tanaka C, Hinse S, Anbarian M, Allard P. Acute effect of orthoses on foot orientation and perceived comfort in individuals with pes cavus during standing. The Foot 2009 19: 1-6.
43. Snow RE, Williams KR. Effects of gait, posture, and center of mass position in women walking in high heeled shoes. Med Sci Sports Exer 1990 22: S23.
44. KA Gillespie, Dickey JP. Determination of the effectiveness of materials in attenuating high frequency shock during gait using filterbank analysis. Clin Biomechanics 2003 18 (1): 50-59.
45. Nigg BM. The role of impact forces and foot pronation: a new paradigm. Clin J Sports Med 2001 11 (1): 2-9.
46. Tippett SR, Voight MJ: Functional Progression for Sport Rehabilitation. Champaigne, IL: Human Kinetics, 1995.