The Foot 24 (2014) 116–122

Contents lists available at ScienceDirect

The Foot

journal homepage: www.elsevier.com/locate/foot

# The impact of different footwear characteristics, of a ballet flat pump, on centre of pressure progression and perceived comfort

Helen Branthwaite[a,*,1], Nachiappan Chockalingam[a,1], Andrew Greenhalgh[a,b,1], Panagiotis Chatzistergos[a,1]

[a] Centre for Sport, Health and Exercise Research, Faculty of Health Sciences, Staffordshire University, Leek Road, Stoke on Trent ST4 2DF, United Kingdom
[b] London Sport Institute, School of Health and Social Science, Middlesex University, Hendon, London NW4 4BT, United Kingdom

ARTICLE INFO

*Article history:*
Received 13 November 2013
Received in revised form 6 May 2014
Accepted 25 May 2014

*Keywords:*
Comfort
Footwear
Bending stiffness
CoP progression
Shoes

ABSTRACT

*Background:* Uncomfortable shoes have been attributed to poor fit and the cause of foot pathologies. Assessing and evaluating comfort and fit have proven challenging due to the subjective nature. The aim of this paper is to investigate the relationship between footwear characteristics and perceived comfort.
*Methods:* Twenty-seven females assessed three different styles of ballet pump shoe for comfort using a comfort scale whilst walking along a 20 m walkway. The physical characteristics of the shoes and the progression of centre of pressure during walking were assessed.
*Results:* There were significant physical differences between each style, square shoe being the shortest, widest and stiffest and round shoe having the least volume at the toe box. Centre of pressure progression angle was centralised to the longitudinal axis of the foot when wearing each of the three shoes compared to barefoot. Length, width and cantilever bending stiffness had no impact on perceived comfort.
*Conclusion:* Wearing snug fitting flexible soled round ballet flat pump is perceived to be the most comfortable of the shoe shapes tested producing a faster more efficient gait. Further investigations are required to assess impact/fit and upper material on perceived comfort to aid consumers with painful feet in purchasing shoes.



## 1. Introduction

The perceived comfort of a shoe may vary across individuals with multiple physical factors being reported as important, such as material properties [1], shoe fit [2], skeletal alignment [3] and fashion [4]. The specific conditions that define a comfortable shoe and therefore good fit are not clear but the most frequent and significant findings for shoe comfort have been attributed to (1) a feeling of support from the upper, (2) foot-bed contact with the foot and (3) stability of the shoe as a whole [5]. Deviations away from any of these parameters may play a considerable role in influencing the perceived comfort level of the shoe, which, has been shown to be considered as a significant factor when purchasing new shoes [11].

Uncomfortable shoes are often attributed to the cause of foot pain and pathology with 60% of female subjects experiencing foot pain related to the shoes worn. Previous research indicates that the most frequent area of discomfort and pain is around the toes, with the population studied having a greater circumference of the metatarsal heads associated to pain [6]. A shoe that is either too loose or too tight can also influence comfort with tissue compression in a snug shoe and slippage or friction in a larger shoe [4]. Observations on shoe wearing habits in the elderly indicates that up to 72% wear shoes that are ill-fitting associated to foot pain and ulceration [7]. Despite the strong evidence to support the notion that ill-fitting footwear can cause foot pain and ulceration, people continue to wear shoes that do not fit the foot [8].

Given that, the individual variations in foot dimension are high, matching the shape of the foot to a suitable shoe style and therefore improving the fit can be challenging. In orthopaedic shoes the profile and depth of the toe box has previously been investigated for its association with increased plantar pressure under the toes [9,10]. Additional toe box depth did not however, improve skin lesion pathology in rheumatoid patients although pain and function scores did improve [10]. This type of orthopaedic shoe with greater toe depth is only worn by a small sample of the

* Corresponding author.
*E-mail addresses:* h.r.branthwaite@staffs.ac.uk (H. Branthwaite), n.chockalingam@staffs.ac.uk (N. Chockalingam), a.greenhalgh@mdx.ac.uk (A. Greenhalgh), Panagiotis.Chatzistergos@staffs.ac.uk (P. Chatzistergos).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.foot.2014.05.004
0958-2592/

population, often elderly, and little is known about the impact shoe styling and manufacturing variations have on the comfort of shoes worn everyday by younger generations.

A previous investigation demonstrated that the shoe of choice for everyday school wear is a flat ballet slip on pump [11]. This unstructured shoe does not provide any fastening or support and can easily fall from the foot on walking and has been previously characterised as a poor fit for patients who suffer from gout [12]. Recommendations for suitable fitting of footwear include (1) the presence of a fastening, (2) firm heel counter, (3) appropriate bending stiffness of the sole and (4) height of the heel [13,14]. According to published research reports, incorrect or poor fitting footwear can be detrimental to the wearer; for example an increase in heel height escalates forefoot plantar pressure [15], altered flare at the toe box being mis-matched to foot shape causing increases in toe pressure [16] and increased risk of falls in the elderly attributed to instability [17].

Footwear stability is most frequently researched within the areas of athletic and high-heeled shoes, with papers mainly focusing on medial and lateral foot stability and postural sway [18–20]. The way the sole is constructed and the sole material properties have been shown to influence stability and comfort in elderly populations with a thick-soled shoe reducing stability and a thinner firmer sole material being more preferable [21]. For heeled shoes though, increased instability is observed when there is a change of heel shape with narrowing of the heel impacting on the medial and lateral centre of pressure progression angle in the frontal plane [22]. Centre of Pressure (CoP) has been identified as the instantaneous point of application of the ground reaction force and the progression of CoP indicates the advances that this point makes during dynamic heel to toe walking [23]. Alterations in CoP progression from the longitudinal axis of the foot can be used to assess foot posture and motion during gait with a medial deviation being associated with a pronated foot type [24]. Motion of the foot whilst wearing shoes is known to provide challenges as the shoe inhibits motion capture [25]. CoP progression can be easily calculated from plantar pressure measurements and has been shown to identify deviations away from the midline of the foot and can be used as a measure of foot function identifying an altered pathway of motion [22,23].

To minimise discomfort and the potential for harm, it is important that a good fitting shoe is essential for everyday wear. The relationship of subjective comfort and the fit of a shoe clearly warrant investigation. Therefore, the primary aim of this paper is to examine the relationship between the perceived comfort whilst wearing three different flat ballet shoes which have an altered forefoot shape, volume and cantilever bending stiffness. Additionally, this study will investigate the impact of CoP progression during walking across these styles.

## 2. Method

### 2.1. Participants

Twenty-seven healthy females, from a convenience sample with an average age of 22.5 (±4.5) years, body mass of 63.3 (±8.9) kg, height of 1.64 (±6.5) m, UK shoe size 5.5 (±0.8), foot length 24.03 cm (±1.3) cm, foot girth – circumference of forefoot – 22.89 (±2.39) cm, and foot posture index 4 (±2), were recruited and provided full informed consent to participate in the study. Ethical approval was sought and granted from the university ethics committee. All subjects included in the study were asymptomatic at the time of testing and were excluded if any musculoskeletal foot and ankle pathologies were present. Foot sizing length and breadth measurements, for correct shoe size allocation, were taken using a Brannock device® (The Brannock Device Company, NY, USA).


**Fig. 1.** Three footwear styles investigated: A4L = square shoe left size 4, B4L = pointed shoe left size 4, C4L = round shoe left size 4.

### 2.2. Footwear characteristics

The style of shoe chosen to investigate was a slip on flat ballet pump. The three toe box shapes were round, square and pointed. This shoe was selected as it has been highlighted as the everyday shoe of choice by young females [11]. All the shoes were black in colour, leather uppers and design on the toe box was matched with a feature of a bow or buckle styling (Fig. 1). The brand of each shoe varied between shoe conditions, with each shoe being purchased from a different retail outlet, and was blinded by covering the logo inside the shoe with micro lining top cover material (Algeos, Liverpool, UK). These features were controlled to minimise preference in brand and design that may influence comfort scores. The heel height on all shoes was standardised to 5 mm, weight of shoe was measured as Square = 192 g, Point = 164 g and Round = 145 g and the sole unit had a smooth tread pattern for each shoe style. The toe box shape and volume of the shoe upper varied between each style

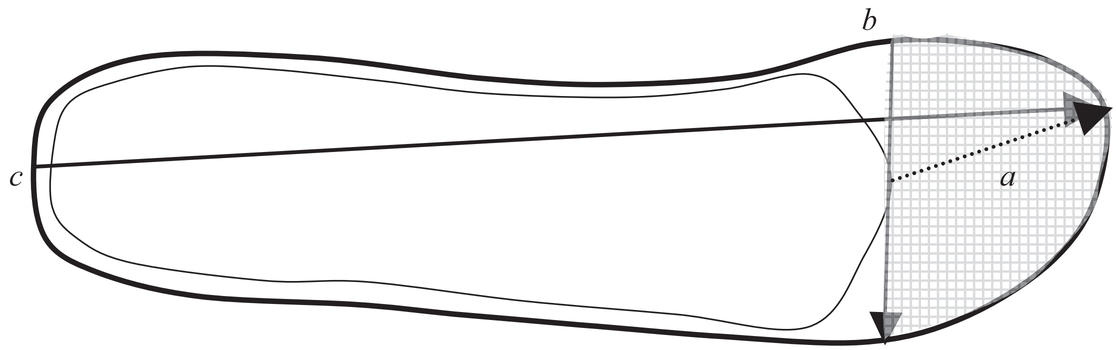


**Fig. 2.** Calculated shoe dimension characteristics: (a) *Volume* from end of shoe to end of vamp – shaded area indicating the volume of the toe box; (b) *breadth* of shoe measured at the widest horizontal point and (c) *length* of shoe measured from the midpoint of the heel to the end of the shoe in the longitudinal plane.

as well as the width and length of each shoe and the cantilever bending stiffness.

The volume of the toe box was measured by calculating the average quantity of a fine substance that filled the toe box to a defined point from the end of the shoe to the throat of the vamp of the shoe. The length of the shoe was defined as the longitudinal measure from the midpoint of the heel to the tip of the shoe and the width as the broadest part of the shoe in the horizontal plane. The averaged value reported for each shoe shape is a mean value for each shoe shape calculated from the four different sizes for each shoe shape used within the study (Fig. 2).

The cantilever bending stiffness was measured as described by Oleson et al. [26]. Four pairs of shoes (eight samples in total) were tested for each shoe style. The samples were individually clamped to a custom made rigid last and loaded on the plantar sole unit with a displacement rate of 2.5 mm/s (Fig. 3). The distance between the bending axis of the shoe and the loading axis of the load frame was equal to 40 mm. Each sample was subjected to two preconditioning load/unload cycles followed by a single loading cycle. No measurement was performed during preconditioning. During the last load cycle the displacement of the piston and the applied force were recorded at 100 Hz and utilised to calculate the value of bending angle and bending moment [26]. After the completion of the tests the initial stiffness (i.e. the initial slope of the moment/angle curve) as well as the work input (i.e. the area under the moment/angle curve) was calculated for each shoe sample (Fig. 3). Work input was calculated for bending angles between 0° and 20°.

## 2.3. Comfort

A 150 mm visual analogue scale was used to assess the comfort characteristics of each shoe [27]. Modifications to the original scale were made to specify different parts of the shoe that were to be assessed as comfortable on a scale of not comfortable at all to most comfortable imaginable. Statements to score on the scale included (1) overall shoe comfort, (2) heel cushioning, (3) ball of the foot cushioning, (4) side to side support, (5) arch height, (6) heel fit, (7) toe box, (8) ball of foot width and (9) length. Subjects were asked to score on the scale how they perceived the comfort of each of the three shoes tested after walking along a walkway of 10 m, turning and returning to the start point covering a total distance of 20 m. This was used as a representation of the distance travelled in a shoe shop when purchasing and trying on new shoes. The maximum comfort for each item was equal to a score of 150 and the minimum 0. The order of shoe allocation was given in a randomised order with each subject choosing a folded card identifying the order of the shoe and barefoot test condition.

## 2.4. Centre of pressure progression

The CoP progression angle was calculated from plantar pressure data that was collected whilst the subject walked the 20 m distance set for comfort assessment. This data were captured using a 1 m pressure plate (Footscan, RsScan Olen, Belgium). The plate was built into the walkway and placed 4 m along a total length of 10 m. This enabled the subjects to attain a normalised walking

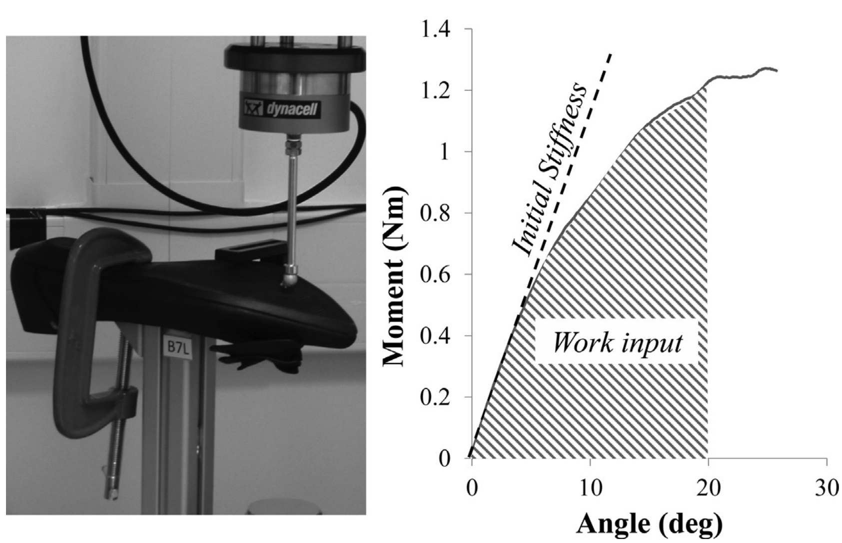


**Fig. 3.** The experimental set-up for cantilever bending tests (left) and a typical bending moment/angle curve (right).

**Table 1**
Shoe characteristics, measures of length, width, volume and bending stiffness with ±SD and significant $p$ values ($p < 0.05$).

| | Length (mm) | Width (mm) | Volume ($mm^3$) | Bending stiffness (N m/deg) | Work input (N m deg) |
|---|---|---|---|---|---|
| Square | 250.75 ± 12.39[†] | 80.75 ± 3.78[†] | 58.75 ± 10.9 | 0.105 ± 0.006[†] | 16.6 ± 1.4[†] |
| Round | 252.5 ± 15.8[‡] | 78 ± 3.91 | 46.25 ± 7.76[‡] | 0.056 ± 0.021 | 10.7 ± 1.6 |
| Point | 258.5 ± 9.81[†,‡] | 78.5 ± 3.11 | 58 ± 10.1 | 0.072 ± 0.010 | 12.5 ± 2.1 |
| *P* value | 0.0005 | 0.0005 | 0.005 | 0.0003 | |

Statistical significance between barefoot and shoe condition shown as *ANOVA $p = <0.05$ and where the difference lies indicated as follows.
[†] Significantly different to round.
[‡] Significantly different to square.
[§] Significantly different to point.

speed prior to data capture and prevent stepping onto the Plate [28]. The data collected were processed using computer programme written specifically for this study using Matlab (r2013a, Mathworks Inc., USA) to calculate the progression angle, contact time and velocity of the centre of pressure at the following times in gait [24]:

- Initial contact phase = ICP (heel strike 0% of stance phase).
- Forefoot contact phase = FFCP (forefoot loading 35% of stance phase).
- Foot flat phase = FFP (midstance 50% of stance phase).
- Forefoot push off phase = FFPOP (toe off 100% of stance phase).

The overall CoP progression angle calculated from the relative CoP displacement was defined as the deflection between the centre of pressure direction and the longitudinal axis of the foot [24].

### 2.5. Data analysis

Comfort for each of the nine individual parameters was scored out of 150 and a total comfort score was calculated for each shoe out of 1350, these scores were then averaged for all subjects. Statistical analysis to test if one shoe was more comfortable than another was completed on comfort scores using a Freidman test ($p \leq 0.05$) looking specifically at differences between conditions for overall comfort, width comfort, toe comfort and length of shoe comfort.

Changes of CoP progression angle from barefoot to wearing shoes were tested with a one way repeated measure ANOVA ($p \leq 0.05$) with post hoc Bonferroni testing. Correlations between comfort and shoe characteristics were evaluated using a Spearman-rho with calculated coefficient of determination and significance levels. Strength of relationships between variables were graded as small when $r = 0.10$–$0.29$, medium when $r = 0.30$–$0.49$ and large 0.5–1.0 [29].

## 3. Results

### 3.1. Footwear characteristics

The shoe characteristics measured showed significant differences between shoe style for length, width, toe box volume and cantilever bending stiffness (Table 1).

### 3.2. Comfort

Between the shoes tested, there was no significant difference in overall comfort ($p = 0.146$). Evaluation of the pointed shoe showed the highest mean overall comfort score at 643 with the round shoe being scored at 635 and square assessed as the least comfortable with an overall mean comfort score of 555, each shoe being scored out of 1350. The square shoe however, was most comfortable in the toe box area with a mean comfort score of 75 with the pointed shoe scoring 69 and round 65 out of 150, but there were no statistically significant differences in comfort when analysed with a Friedman test ($p = 0.495$). Comfort scores for length showed the square shoe to be least comfortable with 68 then point 73 and round 79 out of 150, yet again no significant differences were seen in these results ($p = 0.919$). Similarly, the width of the shoe comfort scores ranked the round shoe being least comfortable with a score of 65, point 69 and square 71 out of 150, these comfort scores were also not significantly different ($p = 0.368$).

### 3.3. Centre of pressure progression

Significant differences ($p \leq 0.05$) were seen in the CoP progression angle between the barefoot condition and all three shoe conditions with the barefoot condition angle being placed medial to the longitudinal axis of the foot (Table 3). The pointed shoe was significantly different to the barefoot and square condition at FFCP (forefoot loading) and the barefoot condition was significantly different to all shoe conditions at FFPOP (toe off) with the COP progression angle moving significantly more lateral to the longitudinal axis of the foot (Fig. 4).

Correlation between comfort and the measured variables (shoe length, width, volume, cantilever bending stiffness and centre of pressure progression angle) are provided in Table 2. There were no statistical significant correlations between comfort scores and shoe characteristics. However, small and medium strength relationships were observed.

**Table 2**
Spearman rank (rho) correlation coefficients for correlation between overall, width, toe box and length comfort scores and individual shoe characteristics. Negative values are showing a negative relationship, strength of relationship determined by position of rank small $r = 0.10$–$0.29$, medium $r = 0.30$–$0.49$ and large $r = 0.50$–$1.0$. Shaded value shows a medium strength relationship although statistical significance was not found.

| Shoe type | Characteristic | Comfort | | | |
|---|---|---|---|---|---|
| | | Overall | Width | Toe box | Length |
| Square | Length | −0.239 | −0.244 | −0.25 | −0.067 |
| | Width | −0.239 | −0.244 | −0.25 | – |
| | Volume | −0.239 | −0.244 | −0.25 | – |
| | Stiffness | −0.126 | −0.176 | −0.162 | – |
| | Cop progress | −0.055 | −0.155 | 0.75 | −0.171 |
| Round | Length | 0.020 | 0.202 | −0.010 | 0.069 |
| | Width | 0.020 | 0.202 | −0.010 | – |
| | Volume | 0.020 | 0.202 | −0.010 | – |
| | Stiffness | 0.357 | 0.182 | 0.117 | – |
| | Cop progress | −0.18 | 0.038 | −0.228 | −0.190 |
| Point | Length | −0.209 | −0.051 | −0.229 | −0.238 |
| | Width | −0.209 | −0.051 | −0.229 | – |
| | Volume | −0.157 | 0.006 | −0.146 | – |
| | Stiffness | 0.209 | 0.051 | 0.229 | – |
| | Cop progress | −0.066 | −0.176 | −0.363 | −0.275 |

**Table 3**
Centre of pressure progression for each of the contact phases for each shoe condition.

| Measurements | Shoe style | | | | |
|---|---|---|---|---|---|
| | Barefoot | Square | Round | Point | *p* value |
| *Time % of COP progression* | | | | | |
| ICP | 10.18 ± 3.34 | 11.08 ± 2.25 | 10.48 ± 4.37 | 11.98 ± 3.31 | 0.137 |
| FFCP | 16.32 ± 9.78 | 17.98 ± 13.5 | 13.99 ± 9.4 | 14.28 ± 9.85 | 1 |
| FFP | 31.15 ± 12.26 | 29.31 ± 14.5 | 38.01 ± 13.15 | 33.33 ± 10.91 | 0.4 |
| FFPOP | 42.65 ± 8.23 | 41.34 ± 8.2 | 36.77 ± 8.7 | 40.02 ± 6.2 | 0.06[*,†] |
| *Progression angle of COP* | | | | | |
| ICP | 3.88 ± 5.05 | −9.67 ± 7.71 | −9.96 ± 7.71 | −15.28 ± 13.11 | 0.005[*,†,‡] |
| FFCP | 4.61 ± 3.27 | 4.29 ± 2.81 | 5.30 ± 2.98 | 7.07 ± 2.77 | 0.004[*] |
| FFP | 1.52 ± 3.27 | 0.31 ± 4.8 | −0.25 ± 2.88 | 0.99 ± 2.85 | 0.147 |
| FFPOP | −13.77 ± 8.5 | −2.10 ± 4.78 | −0.60 ± 4.82 | −2.51 ± 3.9 | 0.005[*,†,‡] |
| *Velocity of COP (cm/s)* | | | | | |
| ICP | 0.45 ± 0.14 | 0.39 ± 0.11 | 0.43 ± 0.13 | 0.34 ± 0.12 | 0.02[*] |
| FFCP | 0.53 ± 0.32 | 0.65 ± 0.4 | 0.63 ± 0.2 | 0.7 ± 0.4 | 0.12 |
| FFP | 0.43 ± 0.18 | 0.43 ± 0.15 | 0.4 ± 0.1 | 0.37 ± 0.1 | 0.1 |
| FFPOP | 0.29 ± 0.04 | 0.32 ± 0.05 | 0.29 ± 0.07 | 0.32 ± 0.06 | 0.26 |
| *Overall Progression angle* | | | | | |
| Progression angle | −2.53 ± 3.46 | −0.59 ± 2.09 | −0.01 ± 1.91 | 0.09 ± 1.62 | 0.01[*,†,‡] |

Statistical significance between barefoot and shoe condition shown as
[*] ANOVA $p = <0.05$ and where the difference lies indicated as follows.
[†] Barefoot significantly different to round.
[‡] Barefoot significantly different to square.
[§] Barefoot significantly different to point.

## 4. Discussion

### 4.1. Footwear characteristics

The most significant measured difference between the shoes was the longitudinal length measured, with each shoe of the same marketed size being significantly different in length to the other. The increased length was mainly due to the alterations in styling at the toe box and was therefore, not a true representation of how the foot sat within the shoe. Although each subject's foot length was matched to the correct shoe size, the impact that the shoe last design and fit had on the individual's foot were not accounted for. This disparity between shoe fit, shoe length and last construction represents an authentic experience for the consumer faced with

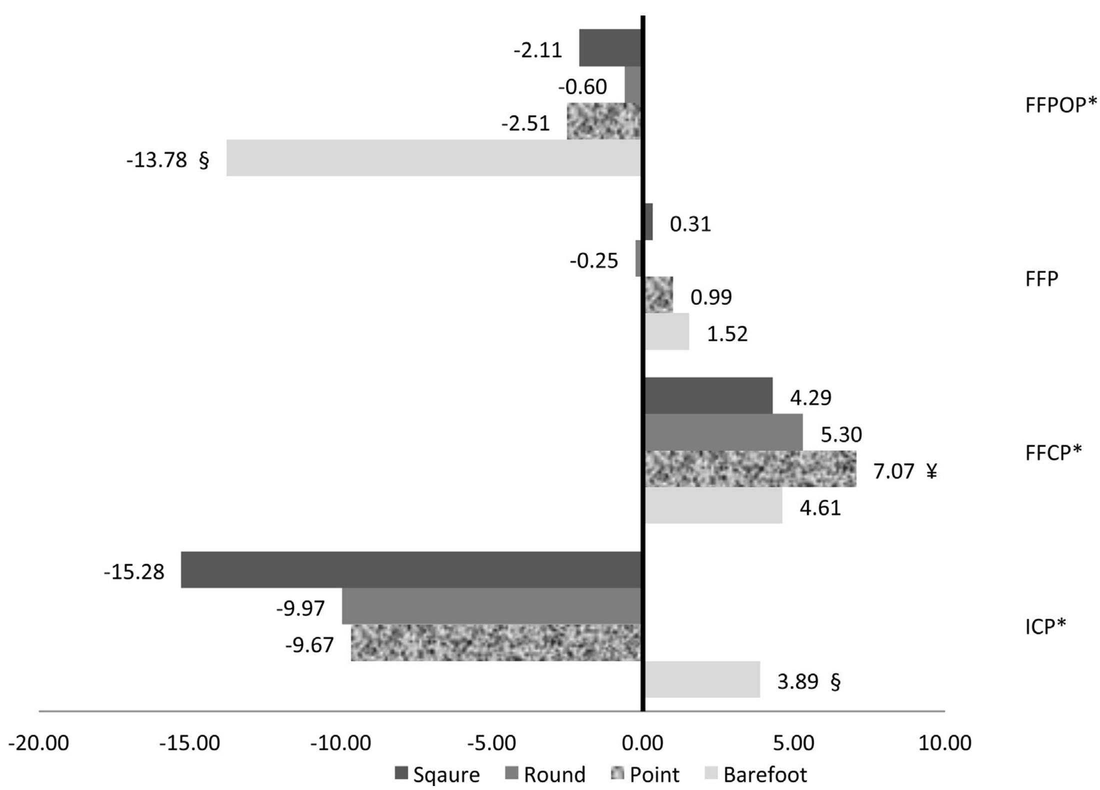


**Fig. 4.** Centre of pressure progression angle for the four phases of gait (ICP, initial contact phase; FFCP, forefoot contact phase; FFP, foot flat phase and FFPOP, forefoot push off phase). A negative value denotes the lateral side from the longitudinal axis of the foot (*significance $p = <0.05$, barefoot significantly different to all shoe conditions, [¥] point significantly different to square and barefoot).

irregular sizing and fit within the shops. Shoe sizing changes have been previously reported within running shoes where the marketed size is not representative of the actual size of the shoe [30]. If consumers are not aware of this sizing error, shoes that are too small or big could be worn without any knowledge by the user contributing to potential pathology [7].

Results from this study clearly indicate the mismatch between the fit and the advertised size of the shoe which has a huge potential to inflict both short and long term foot conditions/pathologies in individuals whom otherwise might not encounter these issues. In this context, the designers and the manufacturers of footwear should pay more attention to improve their product range and clinicians should increase the awareness of sizing issues between styles and manufacturers amongst the population with the choice of footwear.

When evaluating the cantilever bending stiffness of the sole unit of the shoes tested the square shoe was significantly stiffer than the round and pointed shoes. The stiffness of a sole unit is thought to influence foot function giving additional support and is often used in clinical interventions for hallux limitus [31]. However, the square shoe tested, which had the stiffer sole unit, demonstrated a small negative relationship with comfort. Similarly, the least stiff shoe tested was the round toe which had a medium strength positive correlation with comfort indicating that a stiffer soled shoe was least comfortable. All subjects included in this study were assessed as having no musculoskeletal pathologies. The subjects studied were not ailed by any restrictions in joint movement or did not express pain in the metatarsal joints therefore, when this observed normal range of toe flexion occurs a flexible soled shoe is more comfortable. This has been alluded to previously when the shoe has been shown to work with the flexibility and range of motion available in the metatarsophalangeal joints at toe off [26] and when a reduced amount of motion is observed, as in hallux limitus, using a stiffer sole shoe facilitates a relationship between shoe and foot reducing pain associated with pathology. Assessment and advice regarding footwear choice should reflect the individual's metatarsal range of motion when discussing the stiffness of the sole unit.

### 4.2. Comfort

Overall comfort score of the three shoes tested were not significantly different from each other despite the clear differences seen between the physical properties of the shoes. However, the mean overall comfort score for each shoe style failed to reach half way on the scale possibly demonstrating that all three shoes were not necessarily perceived by participants as a comfortable fit.

The ballet pump shoe has recently been downgraded as a desirable "fashion" item to an "essential" clothing item that every female must have, similar to hosiery. Although not through scientific evidence, the shoe is reported to be so popular due to comfort and ease of use that it is now referenced to as a clothing staple [32]. Although the test shoes in this paper were all classed as ballet pumps, they did have different shapes and physical characteristics. To avoid any confounding issues, the test shoes were not compared to the subjects own choice of shoe, neither was the use and individual preference of the ballet pump shoe. Further exploration into whether the test shoes used would have been chosen by subjects as the shoe of choice would help in analysis and discussion of results obtained.

As the chosen test shoes varied in toe box shape and volume, the comfort at the forefoot was investigated specifically to test the notion that a larger volume and broader toe box width would be more comfortable. There was, however no significant correlation between toe box width and volume and the comfort perceived in the toe box area. Although, the round shoe tested did demonstrate a small effect on size yet it was not statistically significant. This small effect could be attributed to the sample size and also variations in the sizing of the shoe. Yet interestingly, the round toe box shoe measured the smallest volume and narrowest width indicating that a smaller volume and width is perceived as more comfortable. Improved contact and sensory feedback from a snugger fitting shoe has been previously attributed to the wearer feeling more comfortable [5] as well as the material used to construct the upper [1]. All the tests shoes were made from leather but the stiffness and softness of the leather was not controlled. The flexibility and suppleness of the round shoe compared to the pointed and square shoe could have improved the comfort perception despite the reduced shoe dimension which may have improved sensory feedback. Footwear upper construction and material properties could therefore play a role in comfort perception of shoes as should be assessed when giving patients footwear advice.

A loose fitting shoe has been reported to alter walking velocity and stride length as the foot alters function in an attempt to keep the shoe on the foot [33]. The lack of fastening from the slip on ballet pump style shoe puts greater emphasis on the shoe needing to be a tighter fit to ensure that the shoe does not fall from the foot whilst walking. The round shoe condition being deemed the tightest shoe in fit with the smallest volume and width did cause a decrease in the duration of the stance phase. The square shoe being the widest and the one with a larger volume resulted in an increase in the duration of the stance phase. This supports the notion that a tight shoe results in a faster and a more efficient gait. Therefore with this style of shoe, subjects were more comfortable and produced a more efficient gait when wearing the smallest width and volume of shoe contradicting advice for footwear fit where emphasis is placed on room in the toe box [34]. The results from this study could help understand why people with foot pathology continue to prefer an ill-fitting shoe [6,8] even though the tightness and fit of the shoe may be contributory factor to foot pain and pathology. Developing further research and footwear design work to provide comfortable fashion shoes that do not contribute to foot pain and pathology would improve foot health particularly in females.

### 4.3. Centre of pressure progression

The influence of a shoe on the CoP progression angle was significant at all the identified events within the stance phase. At ICP (heel strike), there was a dramatic difference between the barefoot and the shoe conditions with all shoes causing an inverted heel strike. However, the participants exhibited a slight eversion during barefoot heel strike. The shoe conditions represent the observations made for normal walking [35] whilst barefoot condition fits to the reported normals seen by young subjects [24]. It is not clear from this study what impact this change has on gait but wearing a flat ballet shoe transforms barefoot walking.

At FFCP (forefoot loading), the pointed shoe was significantly different to the barefoot and square condition, which presented with similar medial deviated angles. It is unclear if any of the measured characteristics can help to discuss these results as the pointed shoe was assessed as being in the middle of the range for the different physical parameters tested. Whilst heel height and sole material were standardised, the contours of the pointed shoe were narrower than the other shoes mimicking the style of a high heel shoe. High heel shoes have previously been shown to alter medial and lateral centre of pressure progression in the frontal plane [22]. The styling of the pointed shoe heel may have resulted in an increased medial shift of the centre of pressure during midstance.

The barefoot condition at FFPOP (toe off) was the most lateral deviated from the longitudinal axis and was significantly different to all shoe conditions. At toe off the impact of wearing this style of shoe brings the CoP progression angle towards the midline of the foot and centralises the body over the foot providing a smoother more efficient locomotion. Further investigations as to whether CoP progression angle reacts this way in all shoe styles would help in the continued investigations and understanding of the effects wearing shoes have on gait, physical wellbeing and pathology.

## 5. Conclusion

The correlation between comfort and all physical characteristics were not statistically significant and only showed medium strength relationships highlighting that the length, width, toe box volume and cantilever bending stiffness of a shoe are not significantly related to the perceived comfort. However, the results indicate that in a popular ballet pump shoe, a snugger fit and more flexible sole unit is perceived to be more comfortable than a stiffer and wider shoe, and produces a more efficient gait, which may contribute to the continued popularity of this shoe choice despite the potential for foot pain and pathology.

## Conflict of interest statement

All authors involved in this research and manuscript preparation have no conflicts of interest that would influence the work or impact the reported results.

## References


[1] Yung-Hui L, Hong WH. Effects of shoe inserts and heel height on foot pressure, impact force, and perceived comfort during walking. Appl Ergon 2005;36(3):355–62.
[2] Witana CP, Feng J, Goonetilleke RS. Dimensional differences for evaluating the quality of footwear fit. Ergonomics 2004;47(12):1301–17.
[3] Miller JE, Nigg BM, Liu W, Stefanyshyn DJ, Nurse MA. Influence of foot, leg and shoe characteristics on subjective comfort. Foot Ankle Int 2000;21(9):759–67.
[4] Au EYL, Goonetilleke RS. A qualitative study on the comfort and fit of ladies' dress shoes. Appl Ergon 2007;38(6):687–96.
[5] Witana CP, Goonetilleke RS, Xiong S, Au EY. Effects of surface characteristics on the plantar shape of feet and subjects' perceived sensations. Appl Ergon 2009;40(2):267–79.
[6] Paiva de Castro A, Rebelatto JR, Aurichio TR. The relationship between foot pain, anthropometric variables and footwear among older people. Appl Ergon 2010;41(1):93–7.
[7] Burns SL, Leese GP, McMurdo MET. Older people and ill fitting shoes. Postgrad Med J 2002;78(920):344–6.
[8] Menz HB, Morris ME. Footwear characteristics and foot problems in older people. Gerontology 2005;51(5):346–51.
[9] Pinzur MS, Slovenkai MP, Trepman E, Shields NN. Guidelines for diabetic foot care: recommendations endorsed by the Diabetes Committee of the American Orthopaedic Foot and Ankle Society. Foot Ankle Int 2005;26(1):113–9.
[10] Cho NS, Hwang JH, Chang HJ, Koh EM, Park HS. Randomized controlled trial for clinical effects of varying types of insoles combined with specialized shoes in patients with rheumatoid arthritis of the foot. Clin Rehabil 2009;23(6):512–21.
[11] Branthwaite H, Chockalingam N, Jones M, Grogan S. Footwear choices made by young women and their potential impact on foot health. J Health Psychol 2013;18(11):1422–31.
[12] Rome K, Frecklington M, Mcnair P, Gow P, Dalbeth N. Footwear characteristics and factors influencing footwear choice in patients with gout. Arthritis Care Res 2011;63(11):1599–604.
[13] Menz HB, Sherrington C. The footwear assessment form: a reliable clinical tool to assess footwear characteristics of relevance to postural stability in older adults. Clin Rehabil 2000;14(6):657–64.
[14] Nácher B, Alemany S, González JC, Alcántara E, García-Hernández J, Heras S, et al. A footwear fit classification model based on anthropometric data. In: Proceedings of the 8th annual digital human modelling for design and engineering symposium, vol. 2327. 2006.
[15] Speksnijder CM, Moonen SA, Walenkamp GH. The higher the heel the higher the forefoot-pressure in ten healthy women. Foot 2005;15(1):17–21.
[16] Goonetilleke RS, Luximon A, Tsui KL. The quality of footwear fit: what we know, don't know and should know. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 44. 2000. p. 2–515.
[17] Sherrington C, Menz HB. An evaluation of footwear worn at the time of fall-related hip fracture. Age Ageing 2003;32(3):310–4.
[18] Robbins S, Waked E, Gouw GJ, McClaran J. Athletic footwear affects balance in men. Br J Sports Med 1994;28(2):117–22.
[19] Brenton-Rule A, Walsh A, Bassett S, Rome K. The evaluation of athletic footwear on postural stability in older adults: an exploratory study. J Foot Ankle Res 2011;4(1):1.
[20] Kilby MC, Newell KM. Intra-and inter-foot coordination in quiet standing: footwear and posture effects. Gait Posture 2012;35(3):511–6.
[21] Robbins S, Gerard JG, McClaran J. Shoe sole thickness and hardness influence balance in older men. J Am Geriatr Soc 1992;40(11):1089.
[22] Chien HL, Lu TW, Liu MW. Control of the motion of the body's center of mass in relation to the center of pressure during high-heeled gait. Gait Posture 2013, http://dx.doi.org/10.1016/j.gaitpost.2012.12.015.
[23] De Cock A, Vanrenterghem V, Willems T, Witvrouw E, De Clercq D. The trajectory of the centre of pressure during barefoot running as a potential measure for foot function. Gait Posture 2008;27(4):669–75.
[24] Chiu MC, Wu HS, Chang LY, Wu MH. Center of pressure progression characteristics under the plantar region for elderly adults. Gait Posture 2013;37:408–12.
[25] Bishop C, Paul G, Thewlis D. Recommendations for the reporting of foot and ankle models. J Biomech 2013, http://dx.doi.org/10.1016/j.jbiomech.2012.06.019.
[26] Oleson M, Adler D, Goldsmith P. A comparison of forefoot stiffness in running and running shoe bending stiffness. J Biomech 2005;38:1886–94.
[27] Mündermann A, Nigg BM, Stefanyshyn DJ, Humble RN. Development of a reliable method to assess footwear comfort during running. Gait Posture 2002;16(1):38–45.
[28] Miller CA, Verstraete MC. Determination of the step duration of gait initiation using a mechanical energy analysis. J Biomech 1996;29(9):1195–9.
[29] Cohen JW. Statistical power analysis for the behavioural sciences. 2nd ed. Hillsdale, NJ, USA: Lawrence Erlbaum Associates; 1988.
[30] Clinghan R, Arnold GP, Drew TS, Cochrane LA, Abboud RJ. Do you get value for money when you buy an expensive pair of running shoes? Br J Sports Med 2008;42(3):189–93.
[31] Smith RW, Katchis SD, Ayson LC. Outcomes in hallux rigidus patients treated nonoperatively: a long-term follow-up study. Foot Ankle Int 2000;21(11):906–13.
[32] Cartner-Morley J. Ballet pumps are so over. In: The guardian; 17 April 2012 http://www.theguardian.com/fashion/2012/apr/17/ballet-pumps-so-over
[33] Doi T, Yamaguchi R, Asai T, Komatsu M, Makiura D, Shimamura M, et al. The effects of shoe fit on gait in community-dwelling older adults. Gait Posture 2010;32(2):274–8.
[34] Williams A. Footwear assessment and management. Podiatry Manage 2007;26(8):165.
[35] Inman VT, Ralston HJ, Todd F. Human walking. Baltimore, USA: Williams & Wilkins; 1981.