OPTIMIZING FOOTWEAR FOR FEMALE FLAG GUARDS: A PLANTAR PRESSURE-BASED DESIGN APPROACH

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OPTIMIZING FOOTWEAR FOR FEMALE FLAG GUARDS: A PLANTAR PRESSURE-BASED DESIGN APPROACH

ABSTRACT. Previous studies on occupational footwear have rarely addressed the biomechanical demands of repetitive high-impact marching in female populations, limiting the generalizability of their conclusions. To address this gap, the study aimed to evaluate the impact of footwear design on plantar pressure distribution and perceived comfort in young female university flag guards during high-impact marching drills, characterised by straight-leg gait patterns and forceful ground contact. Twelve female participants (age: 22.6 ± 3.3 years, ≥1 year of goose-stepping training) performed goose-stepping tasks in three footwear types: Type I (30 mm tapered heel, rigid sole), Type II (47 mm block heel, wider base), and Type III (47 mm block heel, elastic upper, foam insole with varying thickness – 4mm at the forefoot and 7mm at the heel). Plantar pressure was recorded using the Pedar-X system (100 Hz) across eight foot regions during a 30-meter goose-stepping task at 110–116 steps/min. Perceived comfort was assessed via a 100 mm Visual Analog Scale (VAS). Type III significantly reduced peak pressure and pressure-time integral in the central forefoot, lateral forefoot, and heel medial compared to both Type I and II ($P < 0.05$), while also increasing forefoot contact area. Type III received the highest VAS ratings for forefoot cushioning and overall comfort, significantly outperforming Type I ($P < 0.05$). Type II also improved heel cushioning and overall comfort relative to Type I ($P < 0.05$), but was less effective than Type III in forefoot comfort. The Type III design, integrating a wider heel and foam insole with different thicknesses at the forefoot and heel, effectively redistributed plantar pressure and improved comfort, providing evidence-based insights for optimizing footwear to mitigate lower limb injury risks in female flag guards during high-impact ceremonial drills. However, individual differences in foot morphology were not controlled for, which may affect the generalizability of the findings.

KEY WORDS: footwear design, female flag guards, plantar pressure distribution, perceived comfort, goose-stepping

OPTIMIZAREA ÎNCĂLȚĂMINTEI DE DAMĂ PENTRU GARDA DRAPELULUI: O ABORDARE DE DESIGN PE BAZA PRESIUNII PLANTARE

REZUMAT. Studiile anterioare privind încălțămintea de lucru au abordat rareori solicitarea biomecanică a marșurilor repetitive cu impact ridicat la populația feminină, limitând generalizarea concluziilor. Pentru a umple acest gol, studiul de față a avut obiectivul de a evalua impactul designului încălțămintei asupra distribuției presiunii plantare și a confortului perceput la tinerele membre ale gărzii drapelului universitar în timpul exercițiilor de marș cu impact ridicat, caracterizate prin modele de mers cu piciorul drept și contact puternic cu solul. Douăsprezece participante (vârsta: 22,6 ± 3,3 ani, ≥1 an de antrenament pentru „pasul de gâscă") au exersat mersul cu pas de gâscă purtând trei tipuri de încălțăminte: Tipul I (toc conic de 30 mm, talpă rigidă), Tipul II (toc drept de 47 mm, bază mai lată) și Tipul III (toc drept de 47 mm, față elastică, branț din spumă cu grosimi variabile - 4 mm la nivelul antepiciorului și 7 mm la călcâi). S-a înregistrat presiunea plantară utilizând sistemul Pedar-X (100 Hz) în opt regiuni ale piciorului în timpul mersului cu „pas de gâscă" pe o distanță de 30 de metri, la o frecvență de 110-116 pași/min. Confortul perceput a fost evaluat prin intermediul unei scale analogice vizuale (VAS) de 100 mm. Tipul III a redus semnificativ presiunea maximă și integrala presiune-timp în zona centrală a antepiciorului, în zona laterală a antepiciorului și în zona mediană a călcâiului, comparativ cu Tipul I și II ($P < 0,05$), crescând în același timp suprafața de contact a antepiciorului. Tipul III a primit cele mai mari scoruri VAS pentru amortizarea antepiciorului și confortul general, depășind semnificativ Tipul I ($P < 0,05$). Tipul II a îmbunătățit, de asemenea, amortizarea călcâiului și confortul general în comparație cu Tipul I ($P < 0,05$), dar a fost mai puțin eficient decât Tipul III în ceea ce privește confortul antepiciorului. Designul încălțămintei de tip III, care integrează un toc mai lat și o talpă interioară din spumă cu grosimi diferite la nivelul antepiciorului și călcâiului, a redistribuit eficient presiunea plantară și a îmbunătățit confortul, oferind informații bazate pe dovezi pentru optimizarea încălțămintei cu scopul de a atenua riscurile de accidentare a membrelor inferioare la femeile din garda drapelului

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în timpul exercițiilor ceremoniale cu impact ridicat. Cu toate acestea, nu a existat niciun control al diferențelor individuale în ceea ce privește morfologia piciorului, ceea ce poate afecta generalizarea rezultatelor.
CUVINTE CHEIE: designul încălțămintei, garda drapelului, distribuția presiunii plantare, confortul perceput, pas de gâscă

L'OPTIMISATION DES CHAUSSURES FEMME POUR LES GARDES DU DRAPEAU : UNE APPROCHE DE CONCEPTION BASÉE SUR LA PRESSION PLANTAIRE

RÉSUMÉ. Les études antérieures sur les chaussures de travail ont rarement abordé les exigences biomécaniques de la marche répétitive à fort impact chez les femmes, ce qui limite la généralisation de leurs conclusions. Pour combler cette lacune, l'étude visait à évaluer l'impact de la conception des chaussures sur la répartition de la pression plantaire et le confort perçu chez les jeunes femmes membres de la garde du drapeau universitaire lors d'exercices de marche à fort impact, caractérisés par une démarche jambes tendues et un contact puissant avec le sol. Douze participantes (âge : 22,6 ± 3,3 ans, ≥ 1 an d'entraînement au pas de l'oie) ont marché en pas de l'oie avec trois types de chaussures : Type I (talon conique de 30 mm, semelle rigide), Type II (talon bloc de 47 mm, base plus large) et Type III (talon bloc de 47 mm, tige élastique, semelle intérieure en mousse d'épaisseur variable – 4 mm à l'avant-pied et 7 mm au talon). La pression plantaire a été enregistrée à l'aide du système Pedar-X (100 Hz) dans huit régions du pied pendant une marche au pas de l'oie sur une distance de 30 mètres à une fréquence de 110-116 pas/min. Le confort perçu a été évalué via une échelle visuelle analogique (EVA) de 100 mm. Le type III a réduit de manière significative la pression de pointe et l'intégrale pression-temps dans la zone centrale de l'avant-pied, l'avant-pied latéral et le talon médial par rapport aux types I et II ($p < 0,05$), tout en augmentant également la zone de contact de l'avant-pied. Le type III a obtenu les meilleures notes EVA pour l'amorti à l'avant-pied et le confort général, surpassant significativement le type I ($p < 0,05$). Le type II a également amélioré l'amorti au talon et le confort général par rapport au type I ($p < 0,05$), mais s'est avéré moins efficace que le type III pour le confort à l'avant-pied. La conception du type III, intégrant un talon plus large et une semelle intérieure en mousse d'épaisseurs différentes à l'avant-pied et au talon, a efficacement redistribué la pression plantaire et amélioré le confort, fournissant des informations factuelles pour optimiser les chaussures afin de réduire les risques de blessures aux membres inférieurs chez les femmes membres de la garde du drapeau lors d'exercices cérémoniels à fort impact. Cependant, les différences individuelles de morphologie du pied n'ont pas été prises en compte, ce qui pourrait affecter la généralisation des résultats.
MOTS CLÉS : conception de chaussures, garde du drapeau féminin, répartition de la pression plantaire, confort perçu, pas de l'oie

INTRODUCTION

University ceremonial flag guards are required to perform highly regimented marching routines, among which goose-stepping is one of the most biomechanically demanding [1]. Characterized by forceful ground contact, exaggerated knee lifts, and repeated high-impact loading, goose-stepping imposes substantial stress on the musculoskeletal system, particularly the lower limbs and plantar surface [2]. Although marching styles vary across countries, with differences in leg lift angle, stride length, and knee extension, they share common features such as rigid posture, synchronized high-stepping, and significant ground reaction forces [3, 4]. Repeated exposure to such stresses may increase the risk of overuse injuries, including metatarsal stress fractures, patellofemoral pain, and tibial stress reactions. As the foundational interface between the body and the ground, footwear plays a critical role in modulating impact forces, redistributing plantar pressure, and maintaining stability during these ceremonial tasks [5, 6].

Despite their unique functional demands, the ceremonial footwear currently worn by female flag guards in university settings has not been systematically optimized from a biomechanical perspective. These shoes often prioritize visual formal aesthetics—such as elevated heels, tapered designs, and narrow silhouettes—over mechanical functionality. For instance, the typical 30 mm tapered heel combined with a rigid outsole and narrow toe box (Type I shoes) restricts natural foot motion, reduces shock absorption capacity, and increases pressure on the forefoot, especially the metatarsal heads [7-9]. Furthermore, a narrow heel base, which reflects reduced heel base support (HBS) defined as the contact area between the heel and the ground, may compromises postural stability and elevates the risk of ankle injuries during repetitive marching [10].

Prior research has explored the biomechanical implications of occupational footwear in physically demanding environments such as firefighting [11] and industrial work [12, 13]. Modifications like cushioned insoles [14], arch supports [15], and adjustable midsole stiffness [16] have been shown to influence plantar pressure distribution, improve comfort, and reduce injury risks. However, these findings may not be directly transferrable to the context of ceremonial goose-stepping, which involves distinct movement mechanics and aesthetic constraints. Similarly, studies focusing on high-heeled footwear, commonly worn by women in daily or professional settings, have demonstrated adverse effects on plantar pressure, balance, and joint alignment [17-19]. Yet, ceremonial footwear represents a unique hybrid—neither purely functional nor strictly fashionable—and remains under-investigated in biomechanics research.

In particular, the concept of HBS has received increasing attention for its role in maintaining balance and reducing pressure concentrations [20, 21]. A larger HBS can stabilize the foot during heel strike and redistribute forces more evenly across the plantar surface [20]. In addition, insole composition and geometry—including thickness gradients and material compliance—are known to influence both objective pressure parameters and subjective comfort [22, 23], yet are rarely implemented in ceremonial footwear designs.

To address these gaps, this study investigates the biomechanical and perceptual effects of two newly designed ceremonial footwear prototypes for female university flag guards. Type II shoes adopt a wider 47 mm block heel to enhance HBS, while Type III integrates both the wider heel and a foam insole with differential thickness (4 mm at the forefoot and 7 mm at the heel), along with an elastic upper to accommodate dynamic foot deformation. Using in-shoe plantar pressure measurement and subjective comfort assessment, this study systematically assesses their effectiveness by examining: (1) the influence of heel geometry on plantar pressure distribution during goose-stepping, and (2) the impact of increased insole thickness on subjective comfort under repeated impacts. By combining plantar pressure data with perceptual feedback, we seek to deliver evidence-based insights for refining ceremonial footwear, improving both biomechanical efficiency and comfort for personnel in college female flag guards.

MATERIALS AND METHODS

Participants

The required sample size was calculated using G*Power (version 3.1) for a one-way repeated measures ANOVA [24], assuming a large effect size (f = 0.4) based on a pilot study, with a power of 80% and an alpha level of 0.05. The minimum required sample size was determined to be 12. Accordingly, twelve healthy young female university flag guards were recruited for this study (mean age: 22.6 ± 3.3 years; height: 161.9 ± 2.3 cm; body weight: 55.6 ± 6.7 kg; BMI: 21.2 ± 2.6 kg/m^2).

Inclusion criteria were: (1) a minimum of one year of consistent goose-stepping training; (2) no lower limb injuries within the past six months; and (3) participation in at least 10 hours of marching practice per week. Participants were excluded if they had: (1) a history of orthopedic or neurological disorders affecting the lower extremities; (2) difficulty completing the test procedures; or (3) declined to provide written informed consent. The study protocol was approved by the Ethics Committee of Liaocheng University. All participants gave written informed consent before data collection.

Footwear Characteristics

Three types of ceremonial footwear, differing in structural characteristics, were tested in this study (Table 1). All models featured rubber outsoles but varied in heel height, heel base width, and insole thickness. Each participant was provided with properly fitted footwear based on foot length, using standard European shoe sizes ranging from 36 to 39.

Figure 1. Illustration of shoe characteristics measured in the study

Table 1: Design features and material properties of three ceremonial footwear types

Characteristics	Type I	Type II	Type III
Upper Length (mm)	122	161	155
Insole Thickness (mm)	1 (Full-foot)	2 (Full-foot)	Forefoot: 4 Heel: 7
Heel Height (mm)	30	47	47
Heel Width (mm)	19	44.5	44.5
Heel Length (mm)	18	43	43
Outsole Hardness (Shore A)	76-84	Forefoot: 60-65, Heel: 75-80	Forefoot & Waist: 65-75, Heel: 70-80
Weight (g)	223	287	291
Appearance			

Note: Upper length refers to the longitudinal distance from the toe tip to the front edge of the shoe opening (topline). Insole thickness varies by region in Type III. Outsole hardness was measured using the Shore A scale.

Protocol

The overall experimental workflow is illustrated in Figure 2. The Pedar-X in-shoe pressure system (Novel GmbH, Munich, Germany, in Figure 3) was calibrated using the trublu® device, followed by subject-specific static calibration via single-leg stance, indicated by “Unload Left” and “Unload Right” signals on the data logger. Following a 20-minute footwear familiarization period to minimize adaptation effects, participants performed a standardized goose-stepping task along a 30-meter walkway at a cadence of 110–116 steps per minute in Figure 4 [25], following formal drill procedures.

Plantar pressure data were collected using the Pedar-X in-shoe pressure measurement system at a sampling frequency of 100 Hz. Data were collected from each participant’s dominant leg, which was operationally defined as the leg the participant preferred to use for kicking [26, 27]. Each footwear condition was tested in three separate trials. To control for potential fatigue and order effects, a Latin square design was employed to randomize the testing sequence [28]. A 5-minute rest period was provided between trials to reduce cumulative fatigue.

After completing each footwear condition, participants independently rated three aspects of comfort: forefoot cushioning, heel cushioning, and overall comfort. Each was assessed using a separate 100 mm Visual Analog Scale (VAS), with endpoints labeled “extremely uncomfortable” (0 mm) and “extremely comfortable” (100 mm) [29].

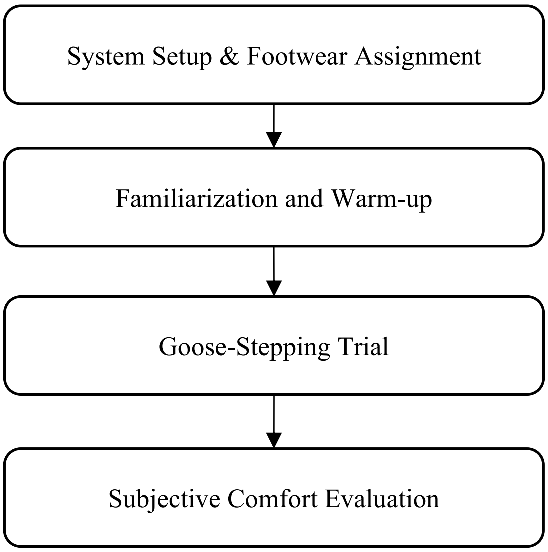


Figure 2. Workflow of the experimental procedure

Figure 3. The Pedar-X in-shoe plantar pressure measurement system used for data collection

Figure 4. Representative posture of a participant during the goose-stepping task

Data Processing

To ensure analysis of steady-state gait, the first and last three steps of each trial (acceleration and deceleration phases) were excluded. The remaining middle 12 consecutive steps were averaged for analysis [30]. Plantar pressure data were segmented into eight anatomical foot regions using the Pedar software's masking function: Hallux (T1), second to fifth toes (T25), medial forefoot (M1), central forefoot (M23), lateral forefoot (M45), midfoot (MF), Heel Medial (HM), and Heel Lateral (HL) (Figure 5). Three key parameters were extracted: Peak Pressure (PP, kPa), Pressure-Time Integral (PTI, kPa·s), and Contact Area (CA, cm^2) [31].

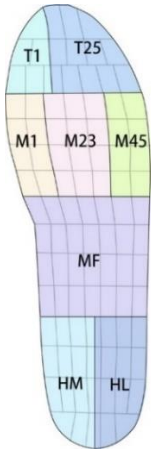


Figure 5. Anatomical division of the plantar surface for pressure analysis in goose-stepping: eight regions defined as Hallux (T1), Second to Fifth Toes (T25), Medial Forefoot (M1), Central Forefoot (M23), Lateral Forefoot (M45), Midfoot (MF), Heel Medial (HM), and Heel Lateral (HL)

Statistical Analysis

All statistical analyses were conducted using SPSS software (version 21.0, IBM Corp., NY, USA). The normality of each variable was verified using the Shapiro-Wilk test. One-way repeated-measures ANOVA was applied to compare plantar pressure variables and VAS comfort ratings across the three footwear conditions. When significant effects were observed, post-hoc analyses were conducted using Tukey's Honestly Significant Difference (HSD) test. In addition to p-values, partial eta squared (η^2p) was calculated to estimate effect sizes for each ANOVA, representing the proportion of variance in the dependent variable explained by the footwear condition. Effect size thresholds were interpreted as small ($\eta^2p \geq 0.01$), medium ($\eta^2p \geq 0.06$), and large ($\eta^2p \geq 0.14$)[32]. The level of significance was set at $\alpha = 0.05$. Data are presented as mean ± standard deviation (SD).

RESULTS

Subjective Comfort Evaluation

Participants' subjective comfort ratings varied significantly across the three footwear conditions. As shown in Figure 6, both Type II and Type III shoes were rated significantly higher in overall comfort compared to Type I (Type I: 47.5 ± 28.3 mm; Type II: 81.7 ± 16.4 mm, P = 0.001; Type III: 80.0 ± 12.8 mm, P = 0.001).

For forefoot cushioning, Type III (62.5 ± 14.9 mm) was rated significantly higher than Type I (44.2 ± 19.8 mm, P = 0.008). For heel cushioning, Type II (60.0 ± 12.8 mm) was significantly superior to Type I (41.7 ± 13.4 mm, P = 0.037). No significant differences were observed between Type II and Type III in any comfort dimension (P > 0.05).

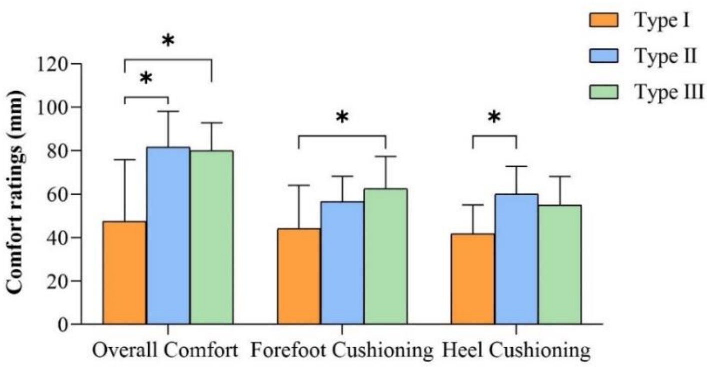


Figure 6. Subjective comfort ratings of three footwear types during high-impact ceremonial drills: forefoot cushioning, heel cushioning, and overall comfort (mean ± SD)

Plantar Pressure Evaluation

The results of the repeated-measures ANOVA for PP, CA, and PTI across eight foot regions are summarized in Table 2, with significant pairwise comparisons visually summarized in Table 3.

Significant differences in PP across footwear types were observed in several plantar regions. Compared with Type I, Type II significantly reduced PP in T1, M23, M45, and HM ($P < 0.05$). Type III showed significantly lower PP than Type I in M23, M45, and HM ($P < 0.05$), but not in T1 ($P > 0.05$). Additionally, PP in M23 and M45 was further reduced in Type III compared to Type II ($P < 0.05$). No significant differences in PP were observed among the three footwear types in T25, M1, MF, or HL ($P > 0.05$).

Consistent with the PP results, both Type II and Type III significantly reduced PTI values relative to Type I in T1, M23, and M45 ($P < 0.05$). No statistically significant differences in PTI were observed between Type II and Type III in any region ($P > 0.05$), nor were there significant effects in the remaining regions (T25, M1, MF, HM, HL).

Differences in CA across footwear types were limited but present in select regions. In M23, Type III exhibited a significantly larger CA than Type I ($P = 0.027$), and in M45, Type III also showed a greater CA than Type II ($P = 0.039$). Conversely, in the Heel Medial (HM), Type II presented a significantly smaller CA compared to Type I ($P = 0.012$). No significant differences were detected in CA in the remaining foot regions ($P > 0.05$).

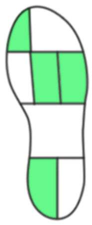
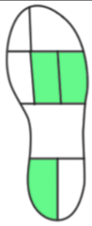
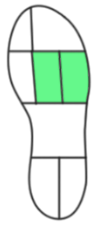
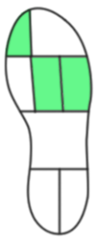
Table 2: Comparison of plantar pressure parameters across eight foot regions among three footwear conditions

Plantar Region	Variables	Type I	Type II	Type III	P value	η^2_p
T1	PP (kPa)	348.55 ± 122.21 [266.4, 430.7]	248.10 ± 113.72^a [166.7, 329.5]	298.20 ± 111.21 [227.5, 368.9]	0.003	0.473
	CA (cm^2)	6.56 ± 0.54 [6.217, 6.903]	6.77 ± 0.46 [6.471, 7.061]	6.76 ± 0.38 [6.516, 7.000]	0.166	0.165
	PTI (kPa·s)	190.45 ± 108.15 [131.9, 274.6]	107.02 ± 60.36^a [76.36, 228.1]	142.84 ± 75.18^a [95.08, 190.6]	<0.001	0.620
T25	PP (kPa)	149.85 ± 54.21 [115.4, 184.3]	147.81 ± 60.68 [109.3, 186.4]	137.71 ± 53.90 [103.5, 172.0]	0.233	0.127
	CA (cm^2)	13.57 ± 1.23 [12.78, 14.35]	13.48 ± 1.34 [12.63, 14.34]	13.34 ± 1.05 [12.67, 14.01]	0.775	0.019
	PTI (kPa·s)	84.41 ± 43.25 [56.94, 111.9]	76.44 ± 35.81 [53.70, 99.20]	75.05 ± 41.25 [48.85, 101.3]	0.093	0.201
M1	PP (kPa)	109.65 ± 28.87 [91.30, 128.0]	96.20 ± 27.18 [78.93, 113.5]	97.31 ± 24.93 [81.47, 113.2]	0.147	0.162
	CA (cm^2)	26.01 ± 3.92 [23.52, 28.50]	24.69 ± 4.22 [22.01, 27.37]	24.41 ± 5.37 [21.00, 27.83]	0.532	0.054
	PTI (kPa·s)	72.27 ± 31.07 [52.51, 92.02]	59.49 ± 30.67 [40.01, 78.98]	63.36 ± 27.82 [45.68, 81.02]	0.049	0.247
M23	PP (kPa)	208.89 ± 33.89 [187.4, 230.4]	179.85 ± 29.04^a [161.4, 198.3]	139.17 ± 36.86^{ab} [115.7, 162.6]	<0.001	0.824
	CA (cm^2)	15.32 ± 1.21 [14.55, 16.09]	15.81 ± 1.37 [14.94, 16.68]	16.36 ± 1.14^a [15.64, 17.08]	0.018	0.312
	PTI (kPa·s)	92.31 ± 28.93 [73.92, 110.7]	75.56 ± 19.47 [63.19, 87.93]	68.45 ± 15.39^a [58.68, 78.23]	0.007	0.409
M45	PP (kPa)	209.71 ± 34.53 [187.8, 231.6]	173.39 ± 29.98^a [154.3, 192.4]	141.03 ± 36.07^{ab} [118.1, 164.0]	<0.001	0.791
	CA (cm^2)	16.34 ± 1.06 [15.66, 17.01]	15.67 ± 1.30 [14.85, 16.50]	16.76 ± 1.01^b [16.12, 17.41]	0.025	0.345
	PTI (kPa·s)	94.38 ± 29.33 [77.23, 114.3]	75.02 ± 22.04 [60.38, 86.88]	72.16 ± 14.29^a [63.09, 81.25]	0.007	0.398
MF	PP (kPa)	253.23 ± 98.51 [190.6, 315.8]	246.20 ± 87.62 [187.3, 305.1]	250.05 ± 124.26 [171.1, 329.0]	0.495	0.143
	CA (cm^2)	10.25 ± 0.50	9.74 ± 1.14	10.02 ± 0.83	0.234	0.126

Plantar Region	Variables	Type I	Type II	Type III	P value	η^2_p
		[9.936, 10.57]	[9.019, 10.46]	[9.500, 10.55]		
	PTI (kPa·s)	102.84 ± 34.20	107.70 ± 44.15	95.19 ± 31.48	0.088	0.161
		[81.11, 124.6]	[83.73, 141.1]	[75.17, 115.2]		
HM	PP (kPa)	276.70 ± 64.64	234.345 ±50.74[a]	222.73 ±55.17[a]	0.001	0.583
		[246.7, 386.9]	[212.2, 303.4]	[196.1, 312.2]		
	CA (cm²)	15.76 ± 0.81	13.70 ± 2.12[a]	14.80 ± 1.87	0.008	0.363
		[15.25, 16.28]	[12.35, 15.05]	[13.61, 15.99]		
	PTI (kPa·s)	132.72 ± 33.32	119.49 ± 37.92	114.32 ± 32.58	0.073	0.225
		[111.6, 153.9]	[95.39, 143.6]	[93.61, 135.0]		
HL	PP (kPa)	120.54 ± 35.22	121.57 ± 47.23	112.70 ± 34.62	0.399	0.077
		[98.15, 142.9]	[91.56, 151.6]	[90.71, 134.7]		
	CA (cm²)	10.33 ± 0.61	9.86 ± 0.85	9.90 ± 1.05	0.322	0.097
		[9.941, 10.72]	[9.321, 10.41]	[9.235, 10.57]		
	PTI (kPa·s)	65.87 ± 26.23	71.79 ± 37.68	72.34 ± 37.85	0.436	0.072
		[49.20, 82.55]	[47.84, 95.74]	[48.29, 96.39]		

Note: Data are presented as mean ± standard deviation. Significant differences (P < 0.05) are indicated by superscripts: a denotes a significant difference compared to Type I, and b denotes a significant difference compared to Type II. PP = Peak Pressure; CA = Contact Area; PTI = Pressure-Time Integral. Foot regions: T1 = Hallux; T25 = Toes 2–5; M1 = Medial Forefoot; M23 = Central Forefoot; M45 = Lateral Forefoot; MF = Midfoot; HM = Heel Medial; HL = Heel Lateral. Brackets "[ ]" indicate 95% confidence intervals.

Table 3: Summary of significant pairwise differences in plantar pressure variables between footwear conditions. Significant values are color-coded for visual clarity

Variables	Type II VS Type I	Type III VS Type I	Type III VS Type II
Peak Pressure (kPa)			
Contact Area (cm²)			
Pressure-Time Integral (kPa·s)			

Note: Green-highlighted regions indicate significantly lower values (P < 0.05), and red-highlighted regions indicate significantly higher values (P < 0.05) compared to the reference footwear, based on statistical results in Table 2. Blank cells represent no significant difference.

DISCUSSION

This study investigated the effects of three ceremonial footwear designs on plantar pressure distribution and subjective comfort in female university flag guards during goose-stepping. The primary findings indicate that the redesigned footwear, particularly Type III, significantly reduced peak plantar pressures and pressure-time integrals in the high-stress forefoot and heel regions and improved perceived comfort compared to the traditional Type I design. These results highlight the biomechanical and perceptual benefits of modifying heel geometry and insole structure in ceremonial footwear.

The most notable reductions in PP and PTI were observed in the M23, M45, and T1 regions when participants wore Type III shoes. These reductions are likely attributable to the combination of two key design elements: a widened block heel and a foam insole with region-specific thickness (4 mm at the forefoot and 7 mm at the heel). Previous research has shown that increased HBS contributes to more stable ground contact and reduced localized pressure during dynamic activities such as running and marching [33, 34]. In our study, both Type II and III designs incorporated a wider 47 mm heel base compared to the 30 mm tapered heel in Type I, resulting in significantly lower PP and PTI values in the heel and forefoot. Although the within-subject design reduced variability, differences in foot morphology may have influenced participants' responses to region-specific sole thickness, which warrants cautious interpretation of the contact area results.

Interestingly, despite the increased heel height in Types II and III, forefoot pressure did not increase. This contrasts with conventional findings in high-heeled footwear research, where elevated heels typically shift the center of mass forward and increase forefoot loading [8, 9, 35]. The absence of this effect in our study suggests that the wider heel base and compliant insole effectively counteracted the pressure concentration normally associated with higher heels. This synergy between structural stability and material compliance supports the notion that optimal footwear performance requires an integrated design approach rather than isolated feature adjustments.

An increased contact area in the M23 and M45 regions suggests enhanced lateral load distribution and foot-ground contact stability during the high-impact midstance and push-off phases of goose-stepping. Type III significantly increased CA in the M23 and M45 regions, suggesting a more even pressure distribution across these regions. An increased contact area has been associated with reduced peak loading, as forces are spread over a larger surface [36, 37]. This finding is consistent with the reduced PP and PTI observed in the same regions. Conversely, Type II reduced CA in the Heel Medial (HM) compared to Type I, despite its wider heel base. One possible explanation is that the rigid outsole and higher heel height of Type II may have limited surface adaptation, thereby reducing effective contact area despite geometric advantages.

These results highlight that contact area is not solely determined by outsole geometry but is also influenced by the flexibility of upper materials, outsole compliance, and foot-shoe interaction during stance. The elastic upper and cushioned midsole of Type III may have facilitated better foot conformity, improving contact in targeted regions.

In addition to biomechanical benefits, both Type II and III footwear were rated significantly higher in subjective comfort compared to Type I, with Type III performing best in forefoot cushioning. This aligns with prior studies reporting that softer, thicker insoles improve user comfort and reduce foot fatigue, especially under repetitive load conditions [38-40]. Notably, comfort perceptions closely mirrored reductions in forefoot PP and PTI, suggesting that localized pressure relief is perceptible and relevant to user experience.

From an application perspective, these findings provide valuable insight into ceremonial footwear design. Traditional dress shoes often prioritize formal aesthetics over function, with narrow heels and rigid soles contributing to discomfort and potential injury. These results suggest that biomechanically informed modifications, including a wider heel base and region-specific cushioning, not only improve immediate comfort and plantar pressure distribution but may also help prevent cumulative stress-related injuries such as metatarsal stress fractures and plantar fasciitis over time. Importantly, these functional enhancements can be achieved without compromising the formal appearance required in ceremonial contexts, demonstrating that a thoughtful balance between visual uniformity and mechanical performance is both feasible and beneficial. In high-impact ceremonial marching, where forces concentrate in specific foot regions, these design improvements offer clear biomechanical advantages.

While this study provides novel insights into the biomechanical and perceptual impacts of ceremonial footwear design, several limitations warrant consideration. First, the sample size was relatively small, which may limit generalizability despite adequate statistical power. Second, only the dominant foot was analyzed, leaving potential asymmetries unexamined. Third, individual biomechanical factors such as foot morphology (e.g., arch height, foot type) and gender-specific characteristics relevant to female participants were not controlled for, which may influence shoe-foot interactions and plantar loading. These factors may influence plantar loading and responses to region-specific sole thickness. Although the within-subject design reduced variability, differences in foot morphology may have influenced participants' responses to region-specific sole thickness, which warrants cautious interpretation of the contact area results. Future studies should incorporate bilateral analysis and stratify participants by foot type, while employing more ecologically valid protocols such as dynamic gait analysis and fatigue testing using continuous motion capture and pressure measurements during prolonged wear.

CONCLUSION

This study investigated the impact of three ceremonial footwear designs on plantar pressure distribution and perceived comfort in female university flag guards during goose-stepping. The results showed that Type III footwear—featuring a widened heel base and region-specific foam insole—significantly reduced peak plantar pressure and pressure-time integral in high-load forefoot and heel regions, while also receiving the highest comfort ratings. Type II, which incorporated only the widened heel, offered moderate improvements compared to the traditional Type I design. These findings suggest that combining structural stability with targeted cushioning can enhance both biomechanical performance and user comfort during high-impact ceremonial activities.

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