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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 exercitiilor de mars 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 paşi/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 priveste confortul antepiciorului. Designul încăltămintei 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 PLANTAIRF

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 goosestepping 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 highstepping, 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 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 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 highheeled footwear, commonly worn by women in daily professional settings,

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 subjective and 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 plantar pressure data 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: 161.9 ± 2.6 kg/m²).

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		4	M

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].

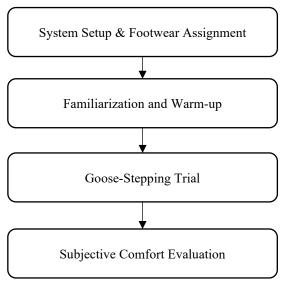


Figure 2. Workflow of the experimental procedure



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, cm²) [31].

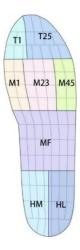


Figure 5. Anatomical division of the plantar surface for pressure analysis in goose-stepping: eight regions defined as Hallux (T1), Second to Fifth Toes (T25), Medial Forefoot (M1), Central Forefoot (M23), Lateral Forefoot (M45), Midfoot (MF), Heel Medial (HM), and Heel Lateral (HL)

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 (n²p) 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 $(\eta^2 p \ge 0.01)$, medium $(\eta^2 p \ge 0.06)$, and large $(\eta^2 p \ge 0.14)[32]$. The level of significance was set at α = 0.05. Data are presented as mean \pm 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 \pm 14.9 mm) was rated significantly higher than Type I (44.2 \pm 19.8 mm, P = 0.008). For heel cushioning, Type II (60.0 \pm 12.8 mm) was significantly superior to Type I (41.7 \pm 13.4 mm, P = 0.037). No significant differences were observed between Type II and Type III in any comfort dimension (P > 0.05).

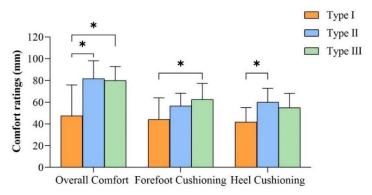


Figure 6. Subjective comfort ratings of three footwear types during high-impact ceremonial drills: forefoot cushioning, heel cushioning, and overall comfort (mean ± SD)

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).

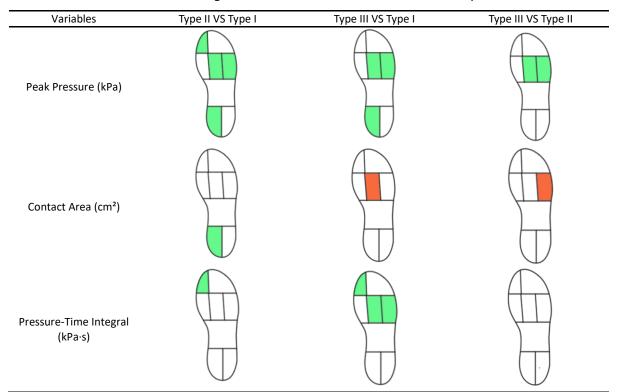
Table 2: Comparison of plantar pressure parameters across eight foot regions among three footwear conditions

Plantar Region	Variables	Type I	Type II	Type III	P value	η^2_p
T1	PP (kPa)	348.55 ± 122.21	248.10 ± 113.72 ^a	298.20 ± 111.21	0.003	0.473
11	rr (Krd)	[266.4, 430.7]	[166.7, 329.5]	[227.5, 368.9]	0.003	0.473
	CA (cm²)	6.56 ± 0.54	6.77 ± 0.46	6.76 ± 0.38	0.166	0.165
	CA (CIII)	[6.217, 6.903]	[6.471, 7.061]	[6.516, 7.000]	0.100	0.103
	PTI (kPa·s)	190.45 ± 108.15	107.02 ± 60.36a	142.84 ± 75.18a	<0.001	0.620
	FII (KFa·S)	[131.9, 274.6]	[76.36, 228.1]	[95.08, 190.6]	<0.001	0.020
T25	PP (kPa)	149.85 ± 54.21	147.81 ± 60.68	137.71 ± 53.90	0.233	0.127
123	FF (KFa)	[115.4, 184.3]	[109.3, 186.4]	[103.5, 172.0]	0.233	0.127
	CA (cm²)	13.57 ± 1.23	13.48 ± 1.34	13.34 ± 1.05	0.775	0.019
	CA (CIII)	[12.78, 14.35]	[12.63, 14.34]	[12.67, 14.01]	0.775	0.019
	PTI (kPa·s)	84.41 ± 43.25	76.44 ± 35.81	75.05 ± 41.25	0.093	0.201
	FII (KFa·S)	[56.94, 111.9]	[53.70, 99.20]	[48.85, 101.3]	0.053	0.201
M1	DD (kDa)	109.65 ± 28.87	96.20 ± 27.18	97.31 ± 24.93	0.147	0.162
IVII	PP (kPa)	[91.30, 128.0]	[78.93, 113.5]	[81.47, 113.2]	0.147	0.102
	CA (cm²)	26.01 ± 3.92	24.69 ± 4.22	24.41 ± 5.37	0.532	0.054
	CA (CIII)	[23.52, 28.50]	[22.01, 27.37]	[21.00, 27.83]	0.332	0.034
	PTI (kPa·s)	72.27 ± 31.07	59.49 ± 30.67	63.36 ± 27.82	0.049	0.247
	PII (KPa·S)	[52.51, 92.02]	[40.01, 78.98]	[45.68, 81.02]	0.049	0.247
M23	PP (kPa)	208.89 ± 33.89	179.85 ± 29.04°	139.17 ± 36.86 ^{ab}	<0.001	0.824
10123	FF (KFa)	[187.4, 230.4]	[161.4, 198.3]	[115.7, 162.6]	\0.001	0.024
	CA (cm²)	15.32 ± 1.21	15.81 ± 1.37	16.36 ± 1.14a	0.018	0.312
	CA (CIII)	[14.55, 16.09]	[14.94, 16.68]	[15.64, 17.08]	0.016	0.312
	PTI (kPa·s)	92.31 ± 28.93	75.56 ± 19.47	68.45 ± 15.39 ^a	0.007	0.409
	FII (KFa·S)	[73.92, 110.7]	[63.19, 87.93]	[58.68, 78.23]	0.007	0.403
M45	PP (kPa)	209.71 ± 34.53	173.39 ± 29.98°	141.03 ± 36.07 ^{ab}	<0.001	0.791
10143	FF (KFa)	[187.8, 231.6]	[154.3, 192.4]	[118.1, 164.0]	<0.001	0.751
	CA (cm²)	16.34 ± 1.06	15.67 ± 1.30	16.76 ± 1.01b	0.025	0.345
	CA (CIII)	[15.66, 17.01]	[14.85, 16.50]	[16.12, 17.41]	0.023	0.343
	PTI (kPa·s)	94.38 ± 29.33	75.02 ± 22.04	72.16 ± 14.29 ^a	0.007	0.398
	r 11 (KFa.2)	[77.23, 114.3]	[60.38, 86.88]	[63.09, 81.25]	0.007	0.330
MF	DD (kDa)	253.23 ± 98.51	246.20 ± 87.62	250.05 ± 124.26	0.495	0.143
IVIF	PP (kPa)	[190.6, 315.8]	[187.3, 305.1]	[171.1, 329.0]	0.493	0.143
	CA (cm²)	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
	PII (KPa·S)	[81.11, 124.6]	[83.73, 141.1]	[75.17, 115.2]	0.000	0.101
НМ	DD (kDa)	276.70 ± 64.64	234.345 ±50.74a	222.73 ±55.17 ^a	0.001	0.583
ПІVІ	PP (kPa)	[246.7, 386.9]	[212.2, 303.4]	[196.1, 312.2]	0.001	0.583
	CA (ama2)	15.76 ± 0.81	13.70 ± 2.12a	14.80 ± 1.87	0.000	0.262
	CA (cm²)	[15.25, 16.28]	[12.35, 15.05]	[13.61, 15.99]	0.008	0.363
	DTI /IcDo. c\	132.72 ± 33.32	119.49 ± 37.92	114.32 ± 32.58	0.072	0.225
	PTI (kPa·s)	[111.6, 153.9]	[95.39, 143.6]	[93.61, 135.0]	0.073	0.225
	DD /I-D=\	120.54 ± 35.22	121.57 ± 47.23	112.70 ± 34.62	0.200	0.077
HL	PP (kPa)	[98.15, 142.9]	[91.56, 151.6]	[90.71, 134.7]	0.399	0.077
	CA (am²)	10.33 ± 0.61	9.86 ± 0.85	9.90 ± 1.05	0.322	0.007
	CA (cm²)	[9.941, 10.72]	[9.321, 10.41]	[9.235, 10.57]	0.322	0.097
	DTI (1.D.)	65.87 ± 26.23	71.79 ± 37.68	72.34 ± 37.85	0.426	0.072
	PTI (kPa·s)	[49.20, 82.55]	[47.84, 95.74]	[48.29, 96.39]	0.436	0.072

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



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 goosestepping. 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 regionspecific 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 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 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 genderspecific 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 regionspecific sole thickness. Although the withinsubject design reduced variability, differences in foot morphology may have influenced participants' responses to region-specific sole thickness, which warrants 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 goosestepping. The results showed that Type III footwear-featuring a widened heel base and region-specific foam insole—significantly reduced peak plantar pressure and pressuretime 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 highimpact ceremonial activities.

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ADVANCED TECHNOLOGIES IN THE DEVELOPMENT OF ANTIMICROBIAL TEXTILES: A REVIEW

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ADVANCED TECHNOLOGIES IN THE DEVELOPMENT OF ANTIMICROBIAL TEXTILES: A REVIEW

ABSTRACT. Textile materials with antimicrobial properties have become increasingly important in various sectors, including healthcare, public transportation, and personal apparel, due to their potential to inhibit the spread of microorganisms. This article reviews the development of antimicrobial textiles, focusing on the integration of advanced technologies such as nanotechnology, plasma treatments, and electrospinning. Specifically, the review explores modern methods including electrospinning, plasma surface functionalization, sol-gel coatings, spray application, microencapsulation, and nanoparticle integration, highlighting their role in improving antimicrobial performance. These methods enhance the antimicrobial efficacy of textiles while maintaining the physical and aesthetic properties of the fabrics. Nanoparticles, particularly silver, have demonstrated significant efficacy against a wide range of pathogens and are used in protective gear and everyday fabrics. KEYWORDS: textile, antimicrobial, antibacterial, electrospinning, nanoparticles

TEHNOLOGII AVANSATE PENTRU DEZVOLTAREA TEXTILELOR ANTIMICROBIENE: O TRECERE ÎN REVISTĂ

REZUMAT. Materialele textile cu proprietăți antimicrobiene au devenit din ce în ce mai importante în diverse sectoare, inclusiv în domeniul sănătății, transportului public și îmbrăcămintei personale, datorită potențialului lor de a inhiba răspândirea microorganismelor. Acest articol analizează dezvoltarea textilelor antimicrobiene, concentrându-se pe integrarea tehnologiilor avansate, cum ar fi nanotehnologia, tratamentele cu plasmă și electrofilarea. Mai exact, analiza explorează metode moderne, inclusiv electrofilarea, funcționalizarea suprafeței cu plasmă, acoperirile sol-gel, aplicarea prin pulverizare, microîncapsularea și integrarea nanoparticulelor, evidențiind rolul lor în îmbunătățirea performanței antimicrobiene. Aceste metode sporesc eficacitatea antimicrobiană a textilelor, menținând în același timp proprietățile fizice și estetice ale țesăturilor. Nanoparticulele, în special argintul, au demonstrat o eficacitate semnificativă împotriva unei game largi de agenți patogeni și sunt utilizate în echipamente de protecție și țesături de zi cu zi. CUVINTE CHEIE: textile, antimicrobian, antibacterian, electrofilare, nanoparticule

TECHNOLOGIES AVANCÉES DANS LE DÉVELOPPEMENT DE TEXTILES ANTIMICROBIENS : UNE REVUE

RÉSUMÉ. Les matériaux textiles aux propriétés antimicrobiennes gagnent en importance dans divers secteurs, notamment la santé, les transports publics et l'habillement, en raison de leur potentiel à inhiber la propagation des micro-organismes. Cet article passe en revue le développement de textiles antimicrobiens, en se concentrant sur l'intégration de technologies avancées telles que la nanotechnologie, les traitements plasma et l'électrofilage. Plus précisément, l'analyse explore les méthodes modernes, notamment l'électrofilage, la fonctionnalisation de surface par plasma, les revêtements sol-gel, la pulvérisation, la microencapsulation et l'intégration de nanoparticules, soulignant leur rôle dans l'amélioration des performances antimicrobiennes. Ces méthodes renforcent l'efficacité antimicrobienne des textiles tout en préservant leurs propriétés physiques et esthétiques. Les nanoparticules, en particulier l'argent, ont démontré une efficacité significative contre un large éventail de pathogènes et sont utilisées dans les équipements de protection et les tissus du quotidien. MOTS-CLÉS: textiles, antimicrobien, antibacterien, électrofilage, nanoparticules

INTRODUCTION

Textiles are ubiquitous and play an essential role in human life, with varied applications ranging from clothing and household products to industrial and medical equipment. Throughout history, textiles have been used not only for protection and comfort, but also as a means of preventing microbial contamination. With the discovery of antibiotics during World War II, antimicrobial textiles began to be used industrially, treated to prevent damage caused by microorganisms and to reduce the risk of infections. This was essential for military equipment, such as tents, tarpaulins, and truck covers, which required

protection against microbial attacks caused by humidity and extreme temperatures. At that time, antimicrobial treatments included antimony salts, copper, and chlorinated wax, which, although effective, had adverse effects on human health and the environment [1].

Today, antimicrobial textiles have become essential in sectors such as medicine, the hospitality industry, public transportation, and sportswear, where controlling the spread of microorganisms is crucial. In medical facilities, for example, gowns, masks, bandages, and bed linens can become vectors for transmitting pathogens, facilitating crosscontamination between patients and medical staff. In addition, in public places such as hotels, restaurants, and public transport,

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frequently used textiles, such as carpets, curtains, and upholstered seats, can be significant sources of infections [1].

Interest in antimicrobial textiles has increased even more with the COVID-19 pandemic, which highlighted the importance of materials capable of reducing viral and bacterial loads. Studies have shown that the SARS-CoV-2 virus can survive on textile surfaces for extended periods, necessitating the development of materials with antiviral, antibacterial, and antifungal properties. Furthermore, in the context of the global health crisis, the use of face masks and personal protective equipment has become essential, emphasizing the need for textiles that are safe, effective, and durable.

Thus, the development of antimicrobial materials has become a continuously expanding research field, integrating advanced technologies such as electrospinning, nanotechnologies, plasma treatments, polymerization, and sol-gel techniques. These methods allow for the creation of textiles with innovative properties such as hydrophobia, fire retardancy, and resistance to microorganisms, opening up new opportunities in biomedical, industrial, and consumer applications [2].

ANTIMICROBIAL TEXTILE TREATMENT METHODS

Antimicrobial treatments applied to textile materials must meet several essential criteria, not just effectiveness against microorganisms. They need to be compatible with textile processes, withstand repeated washings, chemical cleaning, and high temperatures during ironing [3]. They also must be safe for both users and the environment, without compromising the aesthetic or functional properties of the material.

Depending on the composition and structure of the textile fibers, as well as the type of antimicrobial agent used, various chemical and physical techniques have been developed to impart antimicrobial properties to fabrics. One method involves integrating antimicrobial agents into the structure of synthetic fibers during the manufacturing process. Alternatively, for natural and synthetic fibers, antimicrobial treatments can be applied in the finishing stage, in the form of

coatings or impregnations on the textile material surface [4].

These antimicrobial treatments act through two main mechanisms: direct contact or diffusion. In the first case, the antimicrobial agent remains fixed on the fiber surface and acts only upon direct contact with microorganisms. In the case of diffusion, active substances gradually release from the fiber surface or from the textile matrix, attacking microorganisms in the external environment.

To combat microorganisms, antimicrobial agents act by damaging cellular functions. If the antimicrobial treatment only inhibits the development and reproduction of microbes, it has a biostatic effect. Conversely, if the antimicrobial agent is capable of destroying microorganisms, then its effect is considered biocidal [3, 4].

THE USE OF NANOPARTICLES IN ANTIMICROBIAL TEXTILES

Nanoparticles have gained a prominent role in the development of antimicrobial textiles, being applied to both natural and synthetic fibers. Silver nanoparticles (AgNPs), for example, are valued for their effective toxicity against a broad spectrum of microorganisms while maintaining a low level of toxicity towards human cells. Not only do they enhance the durability and color fastness of textile materials, but they have also proven effective in antiviral activities, including against SARS-CoV-2, as indicated by the study of Thi Ngoc Dung *et al.* (2020) [5].

In addition to silver nanoparticles, other types of metal nanoparticles and metal oxides, such as titanium, tin, zinc, gold, and copper, are used for their antimicrobial properties. Copper oxide nanoparticles (CuONPs), for instance, are effective against both Gram-positive and Gram-negative bacteria, according to the study by Rajendran *et al.* (2020) [6], which highlights the complex mechanisms of action including the release of copper ions and the production of reactive oxygen species.

Furthermore, the use of nanoparticles in medical and textile applications is also extending to the development of targeted drug delivery systems, as described by Zhou *et al.* (2020) [7]. These nanoparticles are also involved in the rapid detection of pathogens and in anticancer therapies using labeled

nanoparticles, a field extensively explored by Kennedy *et al.* (2011) [8].

In another study, Liu et al. (2019) [9] highlighted the immobilization of silver nanoparticles on textile fabrics through a radiochemical process, resulting in a material with significant antiviral activity. These findings underline the vast potential of nanoparticles in combating viral, bacterial, and fungal infections and in promoting public health through the development of advanced functional textiles [8].

PROCESSING TECHNIQUES FOR ANTIMICROBIAL TEXTILE MATERIALS

Antimicrobial textiles are materials treated to eliminate or prevent the growth of microbes on the fiber surface. To impart antimicrobial properties to fabrics, numerous finishing and functionalization methods have been developed, including both wet chemical processes and physical surface treatments. Advances in the production of synthetic fibers have facilitated the development of new techniques, as presented in Fig. 1 [8].

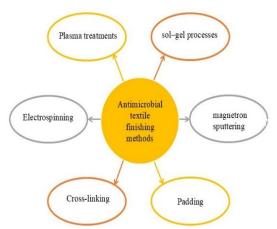


Figure 1. Antimicrobial textile finishing methods

Padding is a conventional textile finishing method where the textile material is uniformly impregnated with an antimicrobial solution, then dried and thermally set (often called the pad-dry-cure process). This technique is particularly suitable for antimicrobial agents in the form of micro/nano particles or polymers with low fiber affinity, requiring a binder or rapid cross-linking at high temperatures (typically 100-150°C for 1-5 minutes) to permanently attach to the material [10]. A successful example of this method is the finishing of cotton with а quaternary ammonium salt-based antimicrobial agent, followed by drying and thermal polymerization. The treated fabric demonstrated excellent bactericidal activity against Staphylococcus aureus and Escherichia coli, maintaining its effectiveness even after 50 washing cycles [11].

Spray-coating involves using a spray device (airbrush) to deposit a fine layer of antimicrobial solution or suspension; in this case, the composition must have low viscosity. The antimicrobial materials applied by spraying range from biocidal polymer solutions to nanoparticle dispersions. For example, the

successful deposition of a luminescent composite based on strontium oxide doped with lanthanides on cotton fabrics has been demonstrated, resulting in a "glow-in-the-dark" material with antibacterial activity against *E. coli, S. aureus,* and *Candida albicans* [12]. Hydrophobic nano-layers with antimicrobial properties were also applied to silk by spraying, using a mixture of silica nanoparticles and quaternary ammonium salts (bactericidal agent) to protect the fiber without compromising its fineness.

The sol-gel method is a wet chemical technology used to create thin oxidative or hybrid layers on the surface of textile materials [1]. The process involves obtaining a colloidal solution of organic precursors (usually metal alkoxides or organomodified polymers) that, through polycondensation, forms a three-dimensional network attached to the textile support. A major advantage of the sol-gel method is the ability to obtain multifunctional coatings: for example, antimicrobial agents and components for UV protection or self-cleaning properties can be simultaneously incorporated into the same film matrix. Metals and metal

oxides are frequently integrated through sol-gel – recent studies have shown the deposition of TiO_2 and ZnO nanoparticles by this process on fabrics, resulting in materials that prevent the development of nosocomial microbes and also exhibit a photocatalytic self-cleaning effect [2].

Plasma treatments constitute a physical, wet-chemical-free method for the surface modification of textiles for the grafting or fixing of functional agents, including antimicrobials. Plasma obtained in a vacuum or at atmospheric pressure creates a reactive environment (ions, free radicals, electrons) that can clean, activate, or nano-structure the fiber surface. Plasma can be used either as a pre-treatment step to the subsequent adherence increase antimicrobial finishes or as a direct method of depositing thin antimicrobial films. In the presence of suitable monomers, plasma can initiate polymerization directly on the textile fiber or chemically graft various types of antimicrobial agents: from organic compounds (chlorinated phenols, triclosan derivatives, quaternary ammonium salts, polymers with guanidine groups, chitosan) to inorganic nanoparticles (Ag, Cu, TiO₂, ZnO). For example, it has been reported that plasma jet and sputtering deposition of nanometric layers of silver, titanium, or copper on textile materials resulted in stable and durable antimicrobial coatings [13].

Microencapsulation is a technology by which the antimicrobial agent is enclosed within a capsule, forming microcapsules [10]. The purpose of microencapsulation is to protect the active substance from external factors and to control its gradual release onto the textile fiber surface. A concrete example is microcapsules with lime essential oil obtained by coacervation using alginate and gelatin as materials. These microcapsules, with an average diameter of ~1.5 µm, were applied to cotton fabric using the pad-dry-cure method, using citric acid as a binder for anchoring. The functionalized fabric thus exhibited high antibacterial activity against skin bacteria, and durability tests showed that only ~3% of the microcapsules detached after 15 washing cycles, with the remainder remaining attached to the fiber [14].

Electrospinning is a modern technology for manufacturing nanometric fibers, which has proven extremely useful for obtaining textile materials with intrinsic antimicrobial properties. The process involves using a strong electric field to extract and solidify fine jets from a polymer solution, thus forming a network of nano/microfibers with a very large specific surface area [15]. This method allows for the direct incorporation of antimicrobial agents into the fiber mass during their formation, resulting in non-woven or fibrous membranes uniformly distributed biocidal activity. For example, it has been demonstrated that electrospun nanofibers from biocompatible polymers loaded with silver nanoparticles or antimicrobial oils can destroy pathogenic bacteria and prevent biofilm formation, highlighting the effectiveness of this strategy for biomedical and environmental applications [15].

Comparative Evaluation of Antimicrobial Finishing Techniques

Electrospinning allows the fabrication of nanofiber webs with extremely high surface area, enabling excellent antimicrobial efficacy due to greater contact with microbes and high loading of biocidal agents. However, electrospinning faces challenges in scalability and mechanical stability – scaling up from lab to industrial production is non-trivial, and electrospun nanofibrous layers can be fragile. Recent studies emphasize that while electrospinning is a promising route for functional textiles, issues of throughput, fiber strength, and cost must be overcome for large-scale use [16].

Plasma treatments, in contrast, are a dry, eco-friendly technology that safely modifies fabric surfaces to enable strong binding of antimicrobial agents without added chemicals. Plasma-based processes create reactive surface functional groups, improving the durability of subsequent antimicrobial finishes by covalently grafting or anchoring biocides onto fibers. The lack of liquid processing chemicals makes plasma a relatively safe and environmentally benign option, although specialized equipment is required and treatment of large fabric rolls at industrial speeds can be a scalability concern [17].

Sol-gel coating techniques offer the benefit of forming inorganic-organic networks on the textile that can entrap antimicrobial compounds in a durable matrix. Finishes applied via sol-gel have demonstrated long-lasting antimicrobial power and wash durability, since biocidal agents (e.g., silver, ZnO) are embedded in a silica or hybrid network that adheres strongly to fiber surfaces. This strong bonding yields controlled release of the antimicrobial and

minimizes leaching during laundering, though careful formulation is needed to avoid brittle coatings. In terms of safety, sol-gel matrices can reduce direct exposure of users to nanoparticles or biocides by immobilizing them, but any nanomaterials used must be assessed for cytotoxicity. Each technology thus balances efficacy with other factors: for instance, electrospun nanofibers can achieve rapid and broad-spectrum microbial kill, yet may require reinforcement for wear; plasma treatments excel in improving bonding and avoiding chemical waste, but often must be combined with an antimicrobial agent to be effective; and sol-gel finishes excel in durability and sustained release, albeit with added process complexity [18].

Practical Applications of Antimicrobial Textile Technologies

Recent advancements highlight the practical implementation of antimicrobial textile technologies, particularly in healthcare and public environments. For instance, hospitals have begun using bed linens, patient gowns, and staff uniforms impregnated with metallic nanoparticles (such as silver or copper) to reduce pathogen transmission. A systematic review reported that textiles treated with copper, silver, zinc oxide, and other agents significantly lowered microbial contamination on fabrics and even reduced healthcareassociated infection rates in clinical use [19]. These antimicrobial healthcare textiles ranging from privacy curtains to surgical scrubs - provide an added line of defense against resistant bacteria in hospital environments. Another prominent example is the development of reusable antimicrobial face masks for public health protection. Innovative masks coated with antiviral nanoparticles (e.g., nano-silver or ZnO) maintained >99% efficacy against bacteria even after 20 laundry cycles, demonstrating excellent durability for repeated use [11]. Such products not only offer personal protection but also address environmental concerns by being reusable. Likewise. researchers recently introduced antimicrobial nanocomposite uniforms and linens that withstood over 100 wash cycles with no loss of functionality [20]. These fabrics, tested against dangerous pathogens like methicillin-resistant S. aureus, remained highly effective after extensive laundering and were verified to be non-irritating to skin. This level of performance suggests that antimicrobial textile innovations are becoming viable for long-term use in hospitals.

CONCLUSIONS

In the context of developing and integrating advanced technologies in textile production, the main goal remains enhancing their functionality in combating microorganisms, a crucial aspect in many sectors of contemporary life. This need has been significantly accelerated by the COVID-19 pandemic, which highlighted the importance of materials capable of reducing viral and bacterial loads. Antimicrobial textiles, through their ability to reduce the spread of infections in medical facilities, public spaces, and even in personal use contexts, represent a promising direction in improving public health standards [16].

The ongoing development of antimicrobial materials integrates techniques such electrospinning, nanotechnologies, plasma treatments, polymerization, and sol-gel methods. These methods enable the creation of textiles with innovative properties such as hydrophobicity, fire retardancy, and resistance to microorganisms, thereby extending potential applications in biomedical, industrial, and consumer domains. Additionally, antimicrobial treatments are designed to be compatible with existing textile processes, withstand rigorous maintenance conditions such as repeated washings and high temperatures, and be safe for users and the environment, without compromising the aesthetic functional properties of the material. A crucial aspect in the use of these technologies is the need for a balance between antimicrobial efficacy and the impact on the environment and human health, avoiding the risk of developing antimicrobial resistance [2, 21].

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3D FOOT MORPHOLOGY AND GENDER DIFFERENCES IN CHINESE YOUTH AGED 17-25

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3D FOOT MORPHOLOGY AND GENDER DIFFERENCES IN CHINESE YOUTH AGED 17-25

ABSTRACT. Accurate understanding of foot morphology is essential for ergonomic footwear design, particularly for young adults whose foot structure may differ from older generations due to lifestyle and nutritional changes. This study aimed to investigate three-dimensional foot morphology and gender differences among Chinese youth aged 17–25. A total of 943 university students (664 males, 279 females) were recruited, and their feet were scanned using a 3D foot scanner. Fifteen key foot dimensions were extracted for analysis. Independent t-tests revealed significant gender-based differences: males tended to have longer and narrower feet, whereas females exhibited higher arches and relatively broader forefeet. Principal component analysis (PCA) identified three main morphological dimensions—length, girth, and height structure. Cluster analysis based on PCA scores classified both male and female feet into three types: slender, standard, and wide. Compared with historical data, modern Chinese youth show increased foot length and girth, suggesting a secular trend. These findings provide updated foot anthropometry data and highlight the necessity for gender- and foot type-specific shoe lasts. This study contributes valuable insights for footwear design, improving product fit, comfort, and reducing the risk of foot-related issues in young adult populations.

KEY WORDS: foot morphology, 3D foot scanning, gender differences, foot shape classification, footwear design

MORFOLOGIA 3D A PICIORULUI ȘI DIFERENȚELE DE GEN LA TINERII CHINEZI CU VÂRSTE CUPRINSE ÎNTRE 17 ȘI 25 DE ANI

REZUMAT. Înțelegerea exactă a morfologiei piciorului este esențială pentru proiectarea ergonomică a încălțămintei, în special pentru tinerii adulți a căror structură a piciorului poate diferi de cea a generațiilor mai în vârstă datorită stilului de viață și a schimbărilor nutriționale. Acest studiu a avut ca scop investigarea morfologiei tridimensionale a piciorului și a diferențelor de gen în rândul tinerilor chinezi cu vârste cuprinse între 17 și 25 de ani. S-au recrutat în total 943 de studenți universitari (664 de bărbați, 279 de femei), iar picioarele acestora au fost scanate folosind un scaner 3D pentru picioare. Cincisprezece dimensiuni cheie ale piciorului au fost extrase pentru analiză. Testele t pentru eșantioane independente au relevat diferențe semnificative în funcție de gen: la bărbații s-a constatat tendința de a avea picioare mai lungi și mai înguste, în timp ce femeile au prezentat arcade plantare mai înalte și zonele anterioare ale piciorului relativ mai late. Analiza componentelor principale (PCA) a identificat trei dimensiuni morfologice principale – lungimea, circumferința și înălțimea. Analiza cluster bazată pe scorurile PCA a clasificat atât picioarele masculine, cât și cele feminine în trei tipuri: subțiri, standard și late. Comparativ cu datele istorice, tinerii chinezi moderni prezintă o lungime și o circumferință ale piciorului crescute, sugerând o tendință seculară. Aceste descoperiri oferă date actualizate despre antropometria piciorului și evidențiază necesitatea unor calapoade specifice sexului și tipului de picior. Acest studiu aduce informații valoroase pentru designul încălțămintei, îmbunătățind potrivirea produsului, confortul și reducând riscul de probleme ale piciorului la populatiile de tineri adulti.

CUVINTE CHEIE: morfologia piciorului, scanare 3D a piciorului, diferențe de gen, clasificarea formei piciorului, designul încălțămintei

LA MORPHOLOGIE 3D DU PIED ET LES DIFFÉRENCES DE GENRE CHEZ LES JEUNES CHINOIS ÂGÉS DE 17 À 25 ANS

RÉSUMÉ. Une compréhension précise de la morphologie du pied est essentielle à la conception de chaussures ergonomiques, en particulier pour les jeunes adultes dont la structure du pied peut différer de celle des générations plus âgées en raison de changements de mode de vie et d'alimentation. Cette étude visait à examiner la morphologie tridimensionnelle du pied et les différences entre les sexes chez les jeunes Chinois âgés de 17 à 25 ans. Au total, 943 étudiants universitaires (664 hommes, 279 femmes) ont été recrutés et leurs pieds ont été scannés à l'aide d'un scanner 3D. Quinze dimensions clés du pied ont été extraites pour analyse. Des tests t indépendants ont révélé des différences significatives selon le sexe : les hommes avaient tendance à avoir des pieds plus longs et plus étroits, tandis que les femmes présentaient des voûtes plantaires plus hautes et des avant-pieds relativement plus larges. L'analyse en composantes principales (ACP) a identifié trois dimensions morphologiques principales : la longueur, la circonférence et la hauteur. L'analyse de cluster basée sur les scores de l'ACP a classé les pieds masculins et féminins en trois types : fins, standard et larges. Comparés aux données historiques, les jeunes Chinois modernes présentent une longueur et une circonférence de pied accrues, suggérant une tendance séculaire. Ces résultats fournissent des données anthropométriques actualisées sur le pied et soulignent la nécessité de formes de chaussures spécifiques au genre et au type de pied. Cette étude apporte des informations précieuses pour la conception de chaussures, améliorant l'ajustement et le confort des produits, et réduisant le risque de problèmes de pieds chez les jeunes adultes.

MOTS CLÉS : morphologie du pied, scan 3D du pied, différences entre les sexes, classification des formes de pied, conception de chaussures

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INTRODUCTION

Ill-fitting shoes affect up to 70% of people worldwide, contributing to discomfort, fatigue, and long-term foot health issues [1]. Accurate foot morphology data are vital for crafting ergonomic footwear that ensures comfort and supports the needs of young adults, whose feet continue to develop into their early twenties [2, 3]. Chinese youth aged 17-25, a significant and expanding segment of the footwear market, may exhibit distinct foot shapes influenced by modern lifestyle changes—such as reduced physical activity [4] and improved nutrition [5]. These factors may differentiate their foot morphology from that of older generations and other populations. However, comprehensive data on this demographic remain scarce, restricting the footwear industry's capacity to design shoes that optimize fit and minimize health risks.

Previous studies highlight that foot morphology varies by gender and ethnicity, with direct implications for shoe design. Results showed that females often have narrower feet and higher arches than males [6, 7], while East Asians, including Chinese populations, tend to have wider forefeet compared to Caucasians of similar lengths [8, 9]. However, previous Chinese foot surveys lack the resolution to reflect the nuanced profiles of today's youth [10], and traditional manual measurement techniques offer limited precision and consistency [11, 12]. These gaps highlight an urgent need for updated, detailed data to meet contemporary design demands. The emergence of 3D scanning technology provides a powerful tool to overcome these limitations [13], delivering precise measurements that can transform how foot morphology is understood and applied in footwear innovation [14].

While prior studies offer valuable insights, they often focus on broader adult populations [8] or use manual measurement techniques [11], leaving the specific foot shape characteristics of Chinese youth

underexplored. This study aims to address this gap by investigating foot morphology in Chinese individuals aged 17-25 using 3D scanning technology. By doing so, it seeks to provide foundational data to inform footwear design tailored to this key demographic, enhancing comfort and supporting foot health in a rapidly evolving market.

MATERIALS AND METHODS

Participants

A total of 943 healthy Chinese university students (664 males, 279 females), aged between 17 and 25 years, were recruited from Shaanxi University of Science and Technology, located in Xi'an, Shaanxi Province, China. The university's student body comprises individuals from various provinces across the country, enabling the recruitment of a demographically diverse cohort representative of Chinese youth.

Participants were recruited between March and June 2024 through university-wide voluntary announcements and sign-up campaigns. A convenience sampling method was employed, considering the logistical practicality of accessing a large student population within a controlled academic environment. Inclusion criteria for participation included the absence of any diagnosed foot deformities (e.g., severe pes planus, hallux valgus), lower limb injuries within the previous six months, and neurological or musculoskeletal disorders that could potentially affect posture, gait, or foot morphology [15]. All participants were screened through self-reported medical histories and a brief physical examination conducted by trained research personnel [16]. Written informed consent was obtained from each participant prior to data collection.

Basic anthropometric data were recorded, including age, body height, body mass, and body mass index (BMI). These characteristics are summarized in Table 1 and are expressed as mean ± standard deviation.

Table 1: Demographic characteristics of study participants by Gender

Variables	Male (n = 664)	Female (n = 279)
Age(years)	19.7 ± 1.7	20.9 ± 1.6
Body height (cm)	176.1 ± 5.8	163.3 ± 17.3
Body mass (kg)	68.2 ± 8.1	55.9 ± 10.4
BMI (kg/m²)	22.0 ± 2.1	21.2 ± 4.2

Note: Data are presented as mean ± standard deviation. BMI = Body Mass Index.

Foot Scanning Procedure

Foot morphology data were collected using the Upod-S 3D foot scanner (Guangzhou Kangyou Technology Co., Ltd., Guangzhou, China), a non-contact laser scanner with a measurement accuracy of ± 0.5 mm and a resolution of 0.1 mm [17, 18]. The scanner was calibrated before each session per manufacturer guidelines to ensure measurement consistency. Scans were conducted in a laboratory maintained at 20–25°C to minimize thermal effects on foot dimensions.

Participants stood barefoot on a rigid platform in a standardized anatomical posture: upright, feet shoulder-width apart, weight evenly distributed, eyes facing forward, and arms relaxed at their sides [12, 19]. This posture replicated natural standing conditions and ensured uniformity across measurements. Both feet were scanned simultaneously under static, full weight-bearing conditions (Figure 1). Each participant was scanned once under static, full weight-bearing conditions [17]. Based on preliminary tests in a 30-subject subsample, intra-device measurement

reliability (ICC) exceeded 0.90 for all dimensions.

Based on prior research and subsample analysis indicating no significant differences between left and right foot measurements (p > 0.05) [20], only right foot data were analyzed to simplify processing and reduce redundancy. This choice aligns with standard practices in foot morphology studies where bilateral symmetry is typically observed in healthy populations.

Foot Measurements

The Upod-S system automatically extracted fifteen key foot dimensions, which encompassed length, width, girth, and height parameters [21]. These included: foot length (heel to the most anterior point of the toes), first and fifth metatarsal lengths, ball width (across the metatarsal heads), metatarsal width, heel width, ball girth, instep girth, heel girth, instep height, hallux height, fifth metatarsal height, navicular height, lateral malleolus height, and medial malleolus height. Each anatomical landmark and corresponding measurement location are depicted in Figure 2.

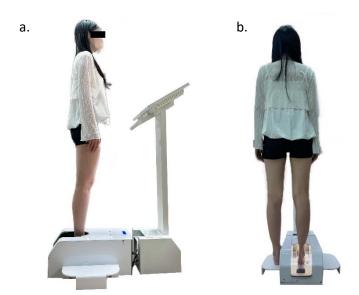


Figure 1. Foot scanning posture

Note: (a) Side view and (b) rear view of the standardized posture using the Upod-S 3D scanner. Participants stood barefoot with feet shoulder-width apart, weight evenly distributed, and maintained an upright posture with eyes forward.

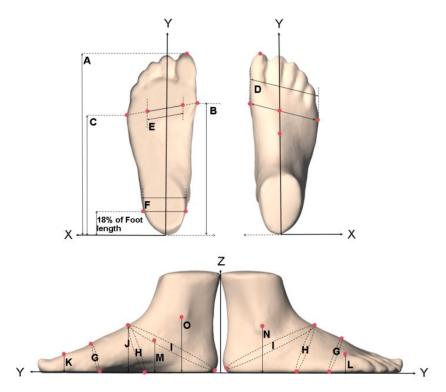


Figure 2. Major indicators of foot structure

Note: The figure depicts foot measurements, including foot length (A), first metatarsal length (B), fifth metatarsal length (C), ball width (D), metatarsal width (E), heel width (F), ball girth (G), instep girth (H), heel girth (I), instep height (J), hallux height (K), fifth metatarsal height (L), navicular height (M), lateral malleolus height (O).

Data Processing

Raw data were first examined using Microsoft Excel (version 16.0) to identify and remove entries with missing values or extreme outliers, based on standardized z-scores (|z| > 3). To ensure consistency and facilitate interindividual comparisons, all 15 foot dimensions were standardized using z-transformation before multivariate analysis [22].

In addition to the z-score normalization, relative dimension standardization was applied to account for individual variations in foot size. Specifically:

Length- and height-related variables (e.g., foot length, instep height, navicular height, hallux height) were normalized using Foot Length (FL) as the base unit [21]:

Relative Value (%FL) =
$$\left(\frac{Dimension}{Foot \ Length}\right) \times 100$$
 (1)

Width- and girth-related variables (e.g., ball width, heel width, ball girth, instep girth, heel girth) were normalized using Ball Girth (BG) as the reference:

Relative Value (%BG) =
$$\left(\frac{Dimension}{Ball\ Girth}\right) \times 100$$
 (2)

These procedures enabled proportional comparisons between participants, allowing gender differences to be interpreted independent of overall foot size.

Statistical Analysis

Statistical analyses were performed using SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics (means and standard deviations) were calculated separately for male and female participants for both absolute and normalized foot dimensions.

Data normality was assessed using the Shapiro–Wilk test (α = 0.05), and homogeneity of variances was evaluated with Levene's test [23]. Two-tailed independent samples t-tests compared gender differences in absolute and normalized dimensions, with a significance threshold of p < 0.05.

To examine the distributional characteristics of Foot Length and Ball Girth by gender, participants were grouped into 5 mm intervals. For each interval, the number of participants within that range was divided by the total number of participants of the same gender to calculate the relative frequency (percentage) [8]. This allowed for visualization of the distribution patterns of foot size characteristics across genders. The resulting distributions were illustrated in histograms to compare male and female trends and to highlight clustering in typical size ranges.

Principal Component Analysis (PCA) was conducted separately for males and females using correlation matrices of standardized variables to explore the underlying structure of foot morphology and reduce dimensionality [24]. Varimax orthogonal rotation enhanced the interpretability of the factor structure. Principal components with eigenvalues greater than 1.0 were retained. PCA scores were used as input

for a two-step cluster analysis. First, Ward's hierarchical clustering method determined the optimal number of clusters. Then, the K-means algorithm refined cluster membership, classifying participants into three foot shape categories (slender, standard, and wide) based on width and thickness indices [25].

RESULTS

Descriptive Statistics of Foot Dimensions

Table 2 showed pronounced and consistent differences in foot morphology between male and female participants across all measured dimensions. Overall, males exhibited significantly larger foot measurements, not only in linear dimensions such as foot length and metatarsal lengths but also in girth and height-related variables. These differences were statistically significant with all p-values below 0.0001.

Dimensions (mm)	Male (n = 664)	Female (n = 279)	t	p value
Foot length	256.1±11.1	237.7±9.5	24.21	<0.0001
First metatarsal length	184.4±7.9	169.0±6.9	28.33	< 0.0001
Fifth metatarsal length	161.3±7.0	147.9±6.0	27.95	< 0.0001
Ball width	100.2±4.4	91.1±4.6	28.60	< 0.0001
Heel width	60.9±3.3	55.2±3.0	24.86	< 0.0001
Metatarsal width	67.1±3.0	61.1±3.1	27.76	< 0.0001
Ball girth	242.7±9.9	221.8±10.2	29.32	< 0.0001
Instep girth	246.0±10.5	220.6±9.9	34.48	< 0.0001
Heel girth	343.4±13.3	313.2±11.9	32.81	< 0.0001
Instep height	68.3 ±4.2	61.7±4.2	22.03	< 0.0001
Hallux height	24.5±2.3	23.2±2.3	7.92	< 0.0001
Fifth metatarsal height	20.8±2.3	19.9±2.2	5.56	< 0.0001
Navicular height	40.7±3.2	37.1±3.0	16.06	< 0.0001
Lateral malleolus height	73.7±5.8	67.4±6.2	14.91	< 0.0001
Medial malleolus height	84.9±4.8	76.4±5.6	23.59	<0.0001

The distribution of foot length (Figure 3) showed that males generally had longer feet, with a peak frequency around 255–260 mm (approximately 20% of males), while females peaked around 235–240 mm (approximately 25% of females), indicating a clear shift toward

smaller foot lengths in females. Similarly, the distribution of ball girth (Figure 4) revealed that males had larger girths, peaking at 240–245 mm (around 20% of males), whereas females peaked at 220–225 mm (around 20% of females).

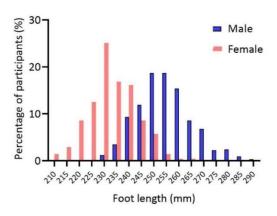


Figure 3. Distribution of foot length among male and female participants

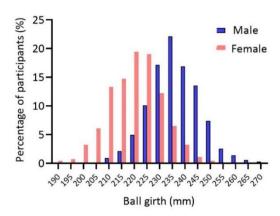


Figure 4. Distribution of ball girth among male and female participants

Gender Differences in Foot Morphology

To explore proportional differences, foot dimensions were normalized to foot length (FL) or ball girth (BG). While absolute dimensions

were consistently larger in males, females exhibited relatively higher arches and wider forefeet. Statistically significant differences were found in nearly all proportional measurements, as shown in Table 3.

Table 3: Gender Differences in Relative Foot Proportions

Dimensions	Male (n = 664)	Female (n = 279)	MD
First metatarsal length (% FL)	72.01±0.13	72.02±0.14	-0.01***
Fifth metatarsal length (% FL)	63.00±0.13	63.02±0.14	-0.02***
Instep height (% FL)	26.72±1.82	26.33±1.87	0.39*
Hallux height (% FL)	9.61±0.96	9.89±1.04	-0.28***
Fifth metatarsal height (% FL)	8.14±0.93	8.47±0.93	-0.33***
Navicular height (% FL)	15.93±1.38	15.80±1.33	0.13*
Lateral malleolus height (% FL)	28.80±2.41	28.72±2.64	0.08*
Medial malleolus height (% FL)	33.21±1.99	32.59±2.42	0.62***
Foot width (%BG)	41.27±0.49	41.06±0.65	0.21***
Heel width (%BG)	25.10±1.12	24.92±1.08	0.18*
Metatarsal width (%BG)	27.64±0.44	27.55±0.54	0.09*
Ball girth (%BG)	94.87±3.91	94.55±4.19	0.32
Instep girth (%BG)	101.35±2.17	99.48±2.23	1.87***
Heel girth (%BG)	141.55±4.47	141.33±4.73	0.22

Note. Data are presented as mean \pm standard deviation. %FL = percentage of Foot Length; %BG = percentage of Ball Girth. MD = Mean difference between male and female values. Significance levels: *p < 0.05, **p < 0.01, ***p < 0.001.

Principal Component Analysis of Foot Dimensions

To reduce dimensionality and explore latent structure, PCA was conducted separately for male and female datasets. Three principal components were extracted, cumulatively explaining over 79% of the

variance in both groups. The components were interpreted as follows:

- PC1: Overall length and longitudinal proportions;
- PC2: Girth and width-related metrics (foot volume);
- PC3: Vertical structure (arch and dorsal height).

Table 4: Results of PCA for male's and female's foot dimensions relative to foot length

Dimensions		Male			Female	
Dimensions	PC1	PC2	PC3	PC1	PC2	PC3
First metatarsal length	0.973	-	-	-	0.962	-
Fifth metatarsal length	0.972	-	-	-	0.962	-
Foot length	0.973	-	-	-	0.962	-
Foot width	-	0.797	-	0.873	-	-
Heel width	-	0.598	-	0.625	-	-
Metatarsal width	-	0.760	-	0.844	-	-
Ball girth	-	0.833	-	0.881	-	-
Instep girth	-	0.755	-	0.787	-	-
Heel girth	-	0.851	-	0.507	-	-
Instep height	-	-	0.082	-	-	0.867
Hallux height	-	-	0.535	-	-	0.618
Fifth metatarsal height	-	-	0.577	-	-	0.798
Navicular height	-	-	0.805	-	-	0.823
Lateral malleolus height	-	-	0.860	-	-	0.812
Medial malleolus height	-	-	0.831	-	-	0.785
Eigenvalue	7.606	2.708	1.598	7.757	2.702	1.506
Variance explained (%)	33.093	24.983	21.340	28.282	28.134	23.349
Cumulative (%)	33.093	58.075	79.415	28.282	56.416	79.765

Cluster-Based Foot Shape Classification

Based on the PCA-derived scores, foot shapes were classified into three morphological categories: Slender, Standard, and Wide. Among both male and female participants, the Standard type was the most common, followed by Wide and Slender types.

Foot thickness was further divided into Thin, Normal, and Thick categories within each

foot shape. In males, Thin feet were relatively uncommon, with Normal and Thick types predominating across all foot shape categories. In females, Thin feet appeared mainly in the Slender and Standard groups, while Wide feet were mostly characterized by Normal and Thick types.

Representative 3D foot shapes classified by width and thickness for young male and female participants are illustrated in Figures 5 and 6, respectively.

Table 5: Distribution of foot thickness types across foot shape clusters by gender

Sex	Туре	Thin (%)	Normal (%)	Thick (%)
NA-1-	Slender	88(13.2%)	94(14.2%)	19(2.9%)
Male	Standard	70(10.5%)	147(22.1%)	71(10.7%)
(n = 664)	Wide	12(1.8%)	69(10.4%)	94(14.2%)
- 1	Slender	27(9.7%)	32(11.5%)	6(2.1%)
Female	Standard	37(13.3%)	68(24.4%)	29(10.4%)
(n = 279)	Wide	9(3.2%)	43(15.4%)	28(10.0%)

Note: Values represent the number of participants and the corresponding percentages in each thickness category (thin, normal, and thick) within each foot shape cluster. Percentages are calculated based on the total number of participants.

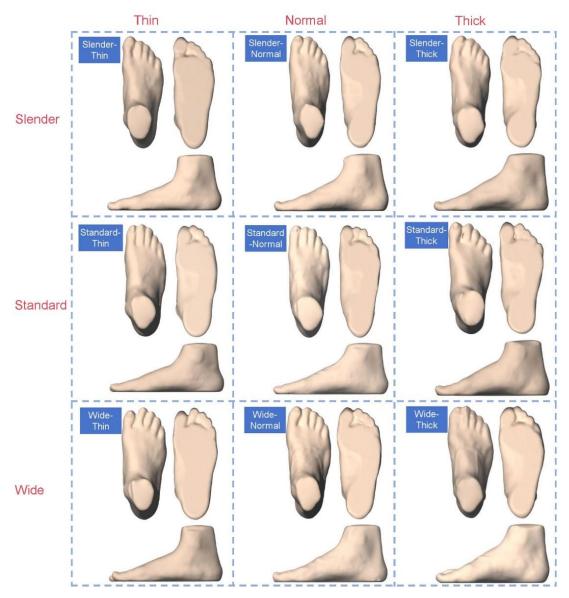


Figure 5. Representative foot shapes classified by width and thickness among young male participants

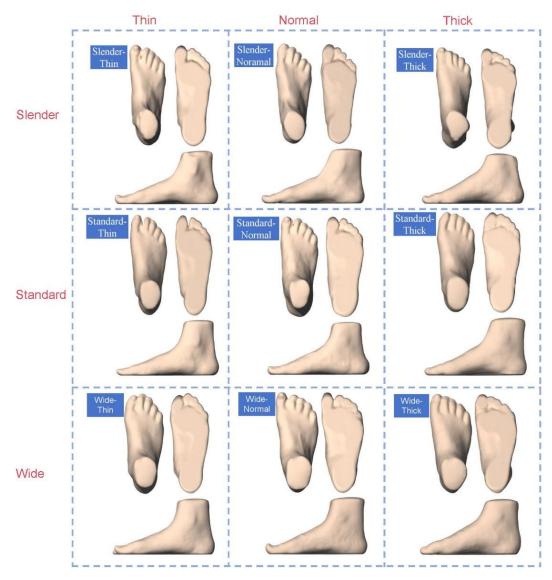


Figure 6. Representative foot shapes classified by width and thickness among young female participants

Comparison with Historical Data

Compared with historical foot dimension data from the 2005 Chinese foot census [10], the current youth cohort exhibited generally larger foot sizes. In both males and females,

increases were observed in overall foot length and ball girth measurements. The most notable differences appeared in foot length, with youth participants showing longer feet than the adult reference population. Increases in ball girth were also present, though to a lesser extent.

Table 6: Comparison with historical Chinese foot census

Sex	Dimension	Current study (mm)	Foot census (mm)	Mean difference (mm)
Male	Foot Length	256.1±11.1	248.9±10.9	7.2
(n = 664)	Ball Girth	242.7±9.9	241.7±11.3	1.0
Female	Foot Length	234.7±9.6	228.8±10.9	5.9
(n = 279)	Ball Girth	221.8±10.3	219.3±11.7	2.5

DISCUSSION

This study provides a detailed analysis of foot morphology in Chinese youth aged 17–25

using 3D scanning technology, offering insights into gender differences, foot shape classifications, and secular trends. The findings have significant implications for footwear design and foot health management,

addressing a critical gap in high-resolution data for this demographic.

Secular Changes in Foot Morphology

The observed increases in foot length (7.2 mm for males, 5.9 mm for females) and ball girth (1.0 mm for males, 2.5 mm for females) compared to historical Chinese data [10] reflect secular trends likely driven by environmental and lifestyle changes. Improved nutrition, particularly increased protein intake, and reduced manual labor due to urbanization are key factors contributing to larger body and foot sizes in modern youth [5, 26]. For instance, studies have linked higher caloric and nutrient increased anthropometric availability to measurements in Chinese adolescents over recent decades [26]. These changes parallel global trends observed in populations with similar socioeconomic shifts, such as in Japan and South Korea [27, 28]. The larger foot dimensions in this cohort suggest that footwear manufacturers must update sizing standards to accommodate contemporary Chinese youth, ensuring comfort and reducing the risk of footrelated disorders caused by ill-fitting shoes.

Regional and Ethnic Comparisons

Within the East Asian context, the foot morphology of Chinese youth appears distinct from that of Japanese and Korean populations, which tend to have shorter and narrower feet [27, 28]. Compared to historical data from Hong Kong, Mainland Chinese youth in this study exhibited more elongated foot profiles [6], possibly due to regional dietary and lifestyle differences. These variations underscore the importance of localized footwear standards, as a one-size-fits-all approach based on broader East Asian data may not adequately serve the Chinese market. While comparisons with Western populations were not a focus of this study, prior research suggests that East Asian feet, including Chinese, are generally shorter but broader with thicker midfoot profiles than Caucasian feet [8, 29, 30]. Future studies could quantify these differences using 3D scanning to inform global footwear design strategies.

Gender Differences and Design Implications

The study highlights distinct gender differences in foot morphology, with females exhibiting relatively higher arches and wider forefeet compared to males. These findings align with prior research indicating that women's feet differ structurally from men's, not merely in size [6, 7]. The higher arches in females suggest a need for shoe lasts with enhanced instep support to prevent discomfort and arch-related issues, such as plantar fasciitis. Similarly, the relatively broader forefeet in females indicate that women's shoes should incorporate wider toe boxes to accommodate forefoot spread during weight-bearing activities.

These gender-specific characteristics challenge the traditional practice of scaling down men's shoe designs for women. Instead, manufacturers should develop distinct lasts that account for proportional differences, particularly in the midfoot and forefoot regions. Such adaptations could reduce the prevalence of foot discomfort, which affects up to 70% of individuals wearing ill-fitting shoes [1], and enhance consumer satisfaction in the growing Chinese footwear market.

Classification of Foot Shape Types

The classification of foot shapes into slender, standard, and wide types, with further subdivision by thickness (thin, normal, and thick), provides a practical framework for footwear design. The predominance of the standard type suggests that most Chinese youth can be accommodated by conventional sizing, but the significant proportions of slender and wide feet highlight the need for diverse size offerings. Notably, the higher prevalence of thick feet in males, particularly in the wide category, indicates a demand for shoes with increased volume in the instep and midfoot areas.

This classification system can optimize inventory management by aligning production with the distribution of foot types, reducing mismatches in retail settings. Additionally, it supports the development of online sizing algorithms, where consumers can select shoes based on their foot shape and thickness profiles. By integrating these classifications into design workflows, manufacturers can

enhance fit precision, improving comfort and reducing returns in e-commerce platforms.

Limitations

Several limitations of this study should be acknowledged. Although the sample was sizable and geographically diverse, all participants were university students from a single institution, which may limit the generalizability of the findings to the broader Chinese youth population. Furthermore, the cross-sectional design offers only a temporal snapshot, preventing analysis of developmental changes in foot morphology over time. Additionally, key lifestyle factors—such as physical activity levels, footwear habits, and occupational demands were not assessed, despite their potential influence on foot structure. To address these gaps, future research should adopt longitudinal designs, include more demographically diverse cohorts, and incorporate relevant lifestyle and environmental variables to achieve a more comprehensive understanding of youth foot morphology.

CONCLUSIONS

This study provides a comprehensive analysis of foot morphology among Chinese youth aged 17-25 using 3D scanning and multivariate statistical methods. The findings reveal significant gender differences and a general increase in foot dimensions compared to historical data, reflecting ongoing secular trends. By classifying foot shapes into slender, standard, and wide types, this research offers practical insights for the development of more anatomically appropriate and comfortable footwear. The results highlight the importance of gender-specific and type-specific shoe lasts to accommodate morphological diversity and improve fit. Moreover, the application of PCA and cluster analysis demonstrates a robust framework for understanding complex foot shape patterns. Although the study is limited by its cross-sectional design and sample source, it establishes a strong foundation for future work. Continued research with broader populations and longitudinal approaches will be critical to optimizing footwear design and promoting foot health in evolving demographics.

Acknowledgements

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ELECTRON BEAM PHYSICAL VAPOR DEPOSITION (EB-PVD): APPLICATIONS ON FLEXIBLE MATERIALS AND POTENTIAL IN THE DEVELOPMENT OF TEXTILE THERMOELECTRIC GENERATORS

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ELECTRON BEAM PHYSICAL VAPOR DEPOSITION (EB-PVD): APPLICATIONS ON FLEXIBLE MATERIALS AND POTENTIAL IN THE DEVELOPMENT OF TEXTILE THERMOELECTRIC GENERATORS

ABSTRACT. Wearable electronics need on-body power sources for extended operation. Thermoelectric generators (TEGs) integrated into textiles are a promising solution, converting body heat into electricity to power wearable sensors and electronics. This approach reduces reliance on batteries and enables fully self-powered wearables. Current flexible TE materials are often conducting polymers or composites, which offer flexibility but have relatively low thermoelectric efficiency. Inorganic semiconductors (e.g., bismuth telluride Bi₂Te₃ and germanium telluride GeTe) provide far higher TE performance, but their rigidity and brittleness hinder direct incorporation into fabrics. Electron beam physical vapor deposition (EB-PVD) provides a way to deposit high-performance inorganic TE films onto flexible substrates. EB-PVD can coat fibers or polymer fabrics with ultrathin Bi₂Te₃ or GeTe layers, transferring the high Seebeck coefficients and conductivity of these inorganics onto a textile platform. However, mechanical and thermal mismatches between stiff films and soft fabrics can cause cracking or delamination under bending and temperature changes. This review summarizes recent advances in the use of EB-PVD for flexible thermoelectric textiles, highlighting both its advantages and current limitations as a deposition method for wearable applications.

KEYWORDS: EB-PVD, TEGs, flexible materials, nanomaterials, textiles

DEPUNERE FIZICĂ ÎN FAZĂ DE VAPORI CU FASCICUL DE ELECTRONI (EB-PVD): APLICAȚII ASUPRA MATERIALELOR FLEXIBILE ȘI POTENȚIAL ÎN DEZVOLTAREA GENERATOARELOR TERMOELECTRICE TEXTILE

REZUMAT. Electronicele purtabile necesită surse de alimentare pe corp pentru o funcționare extinsă. Generatoarele termoelectrice (TEG) integrate în textile reprezintă o soluție promițătoare, transformând căldura corpului în electricitate pentru a alimenta senzori și electronice purtabile. Această abordare reduce dependența de baterii și permite autoalimentarea completă a dispozitivelor purtabile. Materialele TE flexibile actuale sunt adesea polimeri sau compozite conductoare, care oferă flexibilitate, dar au o eficiență termoelectrică relativ scăzută. Semiconductorii anorganici (de exemplu, telurura de bismut Bi₂Te₃ și telurura de germaniu GeTe) oferă performanțe TE mult mai mari, însă rigiditatea și fragilitatea acestora împiedică încorporarea directă în țesături. Depunerea fizică în fază de vapori cu fascicul de electroni (EB-PVD) oferă o modalitate de a depune pelicule TE anorganice de înaltă performanță pe substraturi flexibile. EB-PVD poate acoperi fibrele sau țesăturile polimerice cu straturi ultrasubțiri de Bi₂Te₃ sau GeTe, transferând coeficienții Seebeck ridicați și conductivitatea acestor materiale anorganice pe o platformă textilă. Cu toate acestea, neconcordanțele mecanice și termice dintre peliculele rigide și țesăturile moi pot provoca fisuri sau delaminare la îndoire și la schimbări de temperatură. Această analiză rezumă progresele recente în utilizarea EB-PVD pentru textile termoelectrice flexibile, evidențiind atât avantajele, cât și limitele actuale ale acesteia ca metodă de depunere pentru aplicații purtabile. CUVINTE CHEIE: EB-PVD, TEG-uri, materiale flexibile, nanomateriale, textile

L'ÉVAPORATION PAR FAISCEAU D'ÉLECTRONS (EB-PVD) : APPLICATIONS SUR LES MATÉRIAUX FLEXIBLES ET POTENTIEL DANS LE DÉVELOPPEMENT DE GÉNÉRATEURS THERMOÉLECTRIQUES TEXTILES

RESUME. Les appareils électroniques portables nécessitent des sources d'énergie intégrées au corps pour un fonctionnement prolongé. Les générateurs thermoélectriques (TEG) intégrés aux textiles constituent une solution prometteuse convertissant la chaleur corporelle en électricité pour alimenter les capteurs et les appareils électroniques portables. Cette approche réduit la dépendance aux batteries et permet de créer des appareils portables entièrement autonomes. Les matériaux thermoélectriques flexibles actuels sont souvent des polymères ou des composites conducteurs, qui offrent une certaine flexibilité, mais un rendement thermoélectrique relativement faible. Les semi-conducteurs inorganiques (par exemple, le tellurure de bismuth Bi₂Te₃ et le tellurure de germanium GeTe) offrent des performances thermoélectriques bien supérieures, mais leur rigidité et leur fragilité empêchent leur incorporation directe dans les tissus. Le dépôt physique en phase vapeur par faisceau d'électrons (EB-PVD) permet de déposer des films thermoélectriques inorganiques hautes performances sur des substrats flexibles. L'EB-PVD permet de revêtir des fibres ou des tissus polymères de couches ultrafines de Bi₂Te₃ ou de GeTe, transférant ainsi les coefficients Seebeck élevés et la conductivité de ces matériaux inorganiques à une plateforme textile. Cependant, les disparités mécaniques et thermiques entre les films rigides et les tissus souples peuvent provoquer des fissures ou un délaminage lors de la flexion et des variations et température. Cette revue résume les avancées récentes dans l'utilisation du dépôt EB-PVD pour les textiles thermoélectriques flexibles, soulignant ses avantages et ses limites actuelles comme méthode de dépôt pour les applications portables.

MOTS-CLES : EB-PVD, TEG, matériaux flexibles, nanomatériaux, textiles

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INTRODUCTION

Electron Beam Physical Deposition (EB-PVD) is a vacuum-based coating technology widely used for producing highquality thin films. The process involves bombarding a target material with a focused electron beam generated by a heated filament in a vacuum chamber. The kinetic energy of the electrons is converted into heat upon impact with the target, causing local melting and evaporation of the material; the condensed vapors then deposit a thin layer onto substrates placed nearby. A schematic representation of the EB-PVD process is shown in Figure 1, illustrating the localized heating of the ingot and the direction of sublimated atom flow toward the substrate. However, ordinary textile fibers are dielectric materials and do not inherently attenuate electromagnetic fields. The necessary properties for EMI shielding primarily high electrical conductivity and possibly magnetic permeability-must be imparted through various functionalization methods [2]. This can involve the integration of metallic yarns or fibers, coating fibers with thin metal or conductive polymer layers, impregnating with conductive or magnetic nanoparticles, or developing inherently conductive or magnetic fibers. Essentially, textiles become substrates for functional materials that enable them to reflect or absorb electromagnetic waves [3].

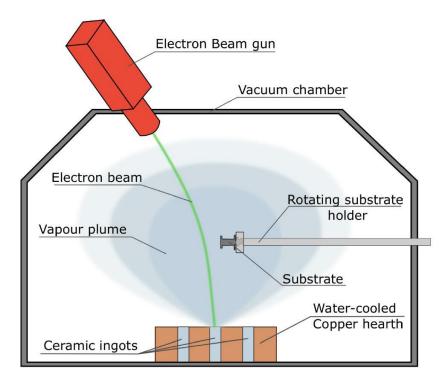


Figure 1. Illustrative diagram of the Electron Beam Physical Vapor Deposition (EB-PVD) process, highlighting the essential components of the setup: electron gun, vacuum chamber, ceramic ingots, rotating substrate holder, and the trajectory of the electron beam [2]

EB-PVD belongs to the category of Physical Vapor Deposition (PVD) processes, which are distinct from Chemical Vapor Deposition (CVD) methods in that they do not involve surface chemical reactions and can operate at lower temperatures [1]. Compared to other PVD techniques, EB-PVD stands out due to its high deposition rates and the high purity of the resulting films. For instance, EB-

PVD can achieve deposition rates on the order of 0.1–100 μ m/min (even up to ~150 μ m/min in certain configurations) owing to the abundant evaporated flux. This allows for uniform coating of substrates, including those with complex geometries, particularly when the substrate is continuously rotated during deposition to ensure even exposure to the vapor stream [3].

Furthermore, the target material utilization efficiency is high, and the process has a reduced environmental impact (it does not produce liquid waste or toxic gases), thus making it a viable alternative to electroplating or other conventional coating techniques [3].

Thanks to these advantages, EB-PVD technology was initially developed and applied in demanding sectors such as the aerospace and energy industries. A notable example is the so-called thermal barrier coatings (TBCs) ceramic thermal protection layers deposited on turbine blades of jet engines. TBCs based on yttria-stabilized zirconia (YSZ) are typically produced via EB-PVD, resulting in a columnar microstructure with oriented porosity that provides excellent resistance to thermal shock and heating/cooling cycles [3, 4]. This type of columnar coating, which cannot be achieved using other methods, exemplifies the EB-PVD process's ability to control microstructural architecture through the adjustment of parameters (substrate temperature, rotation speed, chamber pressure, etc.).

EB-PVD enables Additionally, the fabrication of multilayer structures and functionally graded compositions in a single processing step. For example, the composition of the deposited layer can be varied either continuously or stepwise by using multiple targets, thereby producing functionally graded layers or alternating metal/ceramic structures within the same deposition cycle [4]. This versatility has been demonstrated, instance, in the fabrication of bicomponent thermal barrier coatings (a metallic bond coat of M-Cr-Al-Y and a ceramic YSZ layer) within the same evaporation batch, using a composite ingot designed to sequentially release the metallic and ceramic components [5].

In recent years, researchers have increasingly focused on extending EB-PVD applications beyond traditional domains, aiming at unconventional substrates such as flexible textile materials. Functional textiles represent an emerging direction in materials science, with applications in wearable electronics, embedded sensors in clothing, medical materials, flexible displays, and more. Typically, to impart special properties to textiles (electrical conductivity, antibacterial

activity, hydrophobicity, thermal functionality, etc.), treatments such as nanoparticle impregnation, conductive polymer coatings, or vacuum-based methods like sputtering are employed [6]. However, EB-PVD offers the advantage of producing high-purity, adherent metallic or ceramic thin films without the use of chemical solutions or intermediate synthesis steps. Therefore, integrating EB-PVD into the field of textile materials could open new pathways for the development of smart textiles.

GENERAL PROCESS OF THE EB-PVD METHOD

The EB-PVD process takes place in a high vacuum chamber (typically between 7.5×10⁻⁵ Torr (10^{-2} Pa) in which the source of the material to be deposited and the substrate to be coated are located. The material source is usually a crucible containing the solid target material (metals, alloys, or compounds in ingot form). An electron gun produces the highenergy electron beam required evaporation: electrons are generated by thermionic emission from a heated tungsten filament and are accelerated towards the anode by a potential difference on the order of tens of kV. To focus and deflect the beam towards the target (which is not in a straight line with the filament, to avoid its contamination by vapors), a strong magnetic field is used to bend the trajectory of the electrons [1]. The electrons impact the surface of the target material in a concentrated area, generating an intense heating spot that can temperatures of 2000-3000°C, sufficient to melt and locally vaporize the material almost instantly. A molten bath forms at the surface of the ingot, above which atoms and molecules detach in vapor form. These move ballistically in the rarefied environment and condense on the substrate and on the chamber walls that are in their range of action. Deposition takes place predominantly on surfaces directly exposed to the vapor flux, similar to other PVD processes.

Modern EB-PVD equipment allows fine control of several process parameters to obtain the desired structure of the deposited film: the electron beam power (current and voltage)

controls the evaporation rate; the substrate temperature influences atom mobility and, implicitly, the density and grain size of the layer; residual pressure and the nature of gases in the chamber can affect the microstructure; the rotation speed of the substrate and the device geometry (the incidence angle of vapors) can determine the appearance of inclined or dendritic columnar structures. In addition, some systems include auxiliary sources such as an ion beam directed at the substrate, either for preliminary cleaning of the substrate surface before deposition. All these variables make EB-PVD a complex process, of producing a variety microstructures - from dense, smooth films to highly porous columnar structures - adapted to the target application [4].

An important aspect of the EB-PVD method is the versatility of the materials that can be used for deposition. Practically, any material that can be melted and evaporated in vacuum can serve as a target. Unlike sputtering, which requires electrically conductive targets and has lower yield for materials with high melting point, EB-PVD excels at evaporating refractory materials. Elements with low vapor pressure (e.g.: Mo, W, C) can be efficiently vaporized by the electron beam. Also, ceramic compounds (oxides, nitrides, carbides) can be deposited either by using directly dense ceramic targets (e.g. YSZ), or by evaporating the elemental components from separate crucibles followed by reaction on the substrate (e.g. co-deposition of titanium aluminum in a reactive nitrogen atmosphere to form titanium-aluminum nitride). EB-PVD even allows the realization of alloys or doped layers by simultaneous evaporation from two or more sources with controlled rates. Many industrial EB-PVD systems are equipped with multiple targets that can be brought successively under the beam, allowing layered depositions or the realization of layers with gradually varying composition along the thickness axis (e.g. progressive transition from metallic to ceramic composition in a functionally graded thermal barrier) [2].

Therefore, EB-PVD can produce a wide range of advanced coatings: metallic (e.g. Cu,

Ag, Au films for electronics or decorations), dielectric (SiO₂, Al₂O₃ for optics or insulating layers), superconducting (YBCO in cryogenic electronics), biomaterials (hydroxyapatite on medical implants), etc. The fact that the process takes place in high vacuum ensures the chemical purity of the films (minimal contamination with oxide or moisture) and excellent adhesion, due to the high energy of the condensed atoms and the possibility of ionic pre-cleaning of the substrate. On the other hand, EB-PVD involves expensive equipment and significant energy consumption (high voltage sources, vacuum pumps, cooling systems for targets and chamber walls, etc.). Also, the deposition is directional, which may hinder the uniform coating of substrates with complex geometry if substrate movement is not used. Nevertheless, technical advances have led to EB-PVD systems capable of roll-toroll (R2R) processing of flexible films, making them optimal for high-volume applications such as those in the electronic textile industry. In the following sections we will see how these characteristics of EB-PVD have been exploited to obtain textile materials with functionalities [7].

APPLICATIONS OF THE EB-PVD METHOD ON FLEXIBLE TEXTILE MATERIALS METAL FIBERS AND YARNS INTEGRATION

An important direction in the field of smart textiles is the development of electroconductive textiles, which can serve as sensors, heating elements, antennas, interconnections for wearable electronic devices. Regular textile fibers (natural or synthetic) are electrically insulating, but can be made conductive by depositing a thin metallic layer on their surface. Common methods include chemical metallization (electroplating or electroless plating), coating with conductive inks (printing), or vacuum deposition via sputtering. EB-PVD has also proven effective for textile metallization, offering improved adhesion and uniform coverage. Visileanu et al. [6] reported in 2025 the production of conductive textile structures using an EB-PVD system, depositing copper and silver onto a cotton textile material. The fabric (100%

cotton, density 610 threads/10 cm) was prepared by washing and treating with bonding polymers (an acrylate and a urethane) to improve the continuity of the deposited metallic film. Without this treatment, the metal tended to penetrate between the fibers and failed to form a continuous film due to the roughness and porosity of the textile surface. After treatment, a thin conductive layer was achieved via EB-PVD, with a deposited metal mass of only ~5-7 μg/cm². Characterizations showed that the metallic film covered the fibers uniformly, providing the material with an electrical resistance on the order of ohms per square. Although both copper and silver were effective in imparting conductivity, silver proved more stable under washing and abrasion. The samples coated with Ag by EB-PVD retained a good part of their conductivity even after 5 washing cycles and 5000 abrasion cycles, according to the standard tests conducted by the authors (ISO 105-C06 and ISO 12947). This superior behavior is due both to the high adhesion of the film deposited by EB-PVD and the possible protective role of the polymer treatments applied to the fibers before metallization [6].

A major advantage of using EB-PVD for conductive coatings on textiles is the fineness and conformability of the deposited layer. Metallic films can be achieved with thicknesses of only tens to hundreds of nanometers, sufficient to ensure conductivity without significantly affecting the textile's flexibility, weight, or air permeability [6]. Practically, the coated fiber remains just as flexible, and the layer deforms along with the textile substrate due to its extreme thinness. This is a difference compared to wet methods (e.g., printing with silver paste), where the conductive layer usually has a greater thickness and can weigh down the material. Furthermore, EB-PVD takes place in a clean environment, free of contaminants, which translates to better longterm chemical stability of the films. The mentioned study also investigated and compared DC/RF magnetron sputtering depositions on the same textiles. It was found that both PVD methods provided similar initial conductivity properties, but the adhesion of the sputtered layers was slightly lower than

that of those deposited by EB-PVD in the durability tests under washing. The sputtered films showed small delaminated areas after repeated cycles. This indicates that the higher energy of the atoms deposited by EB-PVD and the possibility of pre-activation of the textile surface (by mild heating or ion bombardment) ensure a closer contact between the film and the substrate [6].

Beyond copper and silver, EB-PVD can be used to evaporate and deposit a variety of conductive metals or alloys on textile materials, depending on the application. For example, for electromagnetic screens, aluminum or nickel films can be deposited; for flexible electrical circuits, gold or copper-gold alloys may be used. A particular case of practical interest is antibacterial coatings on medical or hygienic textiles. Silver and copper ions are well known for their antimicrobial action, which is why these metals are often incorporated into textiles intended for medical equipment (gowns, bedding, bandages) or sports equipment. The PVD method allows the uniform application of a very thin layer of Ag or Cu on the surface of textile fibers, giving them long-lasting antibacterial properties [8, 9]. Scholz et al. investigated the antimicrobial properties of fabrics coated with precious metals (Ag, Au, Pt) by vacuum sputtering [10]. The metallized fabrics showed a significant reduction in bacterial load (including Staphylococcus aureus) compared to uncoated textiles, showing potential for applications in the medical field. Although that study used sputtering, it can be suggested that silver deposition via EB-PVD would have similar effects, considering the chemically inert nature of the process and the purity of the resulting layer. A nanometric layer of silver deposited on fibers can continuously release Ag ions under the action of moisture, preventing bacterial proliferation on the material's surface. Moreover, compared to chemical treatments (which may include the reduction of Ag compounds directly on the fiber, generating nanoparticles), the PVD method ensures stronger fixation of silver on the substrate, which translates to higher resistance to multiple washes. Thus, EB-PVD emerges as an effective solution for producing durable antibacterial textiles, without resorting to potentially harmful or costly chemicals [10].

The application of the EB-PVD method to textile materials has proven feasible for obtaining conductive and functional textiles. The key to success lies in the proper preparation of the textile surface (cleaning, activation, or coating with a polymer primer) so that the fibers, which are flexible and porous, can support the formation of a continuous film. The literature results indicate that textiles metallized by EB-PVD can meet demanding performance requirements (conductivity, wear resistance, chemical stability), paving the way for their integration into wearable electronic devices. In the next section, we will explore an advanced application of these conductive textiles: textile thermogenerators, which convert heat directly into electrical energy.

EB-PVD APPLICATIONS IN THE DEVELOPMENT OF TEXTILE THERMOGENERATORS

Textile thermogenerators are flexible devices integrated into textile-like structures, designed to generate electrical energy by exploiting temperature differences, example, between the human body and the ambient environment. They are based on the Seebeck thermoelectric effect: when there is a temperature gradient between the ends of a semiconductor element, an electric voltage is generated. By connecting multiple n-type and p-type thermoelectric elements in series, a generator capable of supplying direct current is created. Interest in wearable thermogenerators is high, as they can provide continuous power to body-worn sensors and electronic devices, eliminating dependence on conventional batteries. Unlike other portable energy sources (photovoltaics, which depend on sunlight, or kinetic generators, which require movement), thermogenerators can function passively by using body heat, offering a green and silent energy source as long as there is a temperature difference [7].

The challenge in creating textile thermogenerators lies in integrating thermoelectric (TE) materials—which are often fragile, inorganic, and require high processing

temperatures—with flexible textile substrates, without compromising the TE performance or the wearability of the system. Numerous studies have addressed this issue through various strategies: incorporating thermoelectric fibers into the fabric (e.g., knitted binder fibers containing Bi₂Te₃ powders), depositing thermoelectric ink on textiles (by printing or dyeing with conductive organic compounds and TE nanoparticles), or laminating thin thermoelectric films onto textile supports. In this context, EB-PVD offers a promising approach, enabling the direct deposition of inorganic thermoelectric materials as thin films on flexible substrates, with precise control over thickness and composition [11, 12].

A demonstrative example of the potential of PVD in flexible thermogenerators is provided by Morgan et al. (2019), who fabricated thermoelectric generators polymeric substrates using roll-to-roll compatible PVD techniques. In this study [7], the authors deposited a layered Bi₂Te₃/GeTe TEG system onto a thin polyimide ribbon via sputtering, magnetron achieving thermoelectric leg-pair with a Seebeck coefficient of ~140 µV/K and a power output of ~0.4 nW per module at a temperature difference of 20 K. Additionally, they demonstrated a new high-productivity PVD instrument based on a pulsed electron beam, called Virtual Cathode Deposition (VCD), with which they rapidly deposited Bi₂Te₃/GeTe TEG films. The thermogenerator thus produced reached a Seebeck coefficient of ~250 μV/K per pair and ~0.2 nW per pair at a 20 K temperature difference. These results, although at the laboratory level, are encouraging—they show that PVD techniques (including electron beamproduce ones) can functional thermoelectric devices on flexible substrates, with performances comparable to those obtained by classical methods on rigid substrates [7].

The direct application of EB-PVD in the fabrication of textile thermogenerators would involve the deposition of thermoelectric materials onto a textile support or onto intermediate layers applied to the textile. A practical possibility would be the use of a

thermostable textile material as a support, capable of being introduced into the EB-PVD chamber. Alternatively, textile fibers could be individually coated with TE material, then integrated into a woven or knitted structure. In either case, EB-PVD would offer the advantage of obtaining crystalline TE films with wellcontrolled composition [13]. EB-PVD deposition of thermoelectric materials has already been explored on rigid substrates to optimize microstructure. Smith et al. (2009) fabricated a thermoelectric microgenerator composed of thin Si/SiGe networks, sequentially deposited by EB-PVD on silicon, followed by high-energy Si ion irradiation. The ion bombardment reduced the thermal conductivity of the network and increased the leading Seebeck factor, to improved thermoelectric conversion efficiency. This example demonstrates that EB-PVD can produce advanced thermoelectric structures and that post-deposition treatments, such as doping or irradiation, can be applied to enhance performance [13].

To utilize these advantages in a textile thermogenerator, a few technical obstacles still need to be overcome. First, the thermal compatibility of the textile substrate with the process: many textile fibers (cotton, polyester) degrade or decompose begin to temperatures above 200°C, and in EB-PVD, substrates can reach such temperatures either through thermal radiation from the target or intentionally, for film crystallization. Possible solutions include keeping the substrate at low temperature via active cooling of the substrate holder, or using high-temperature-resistant polymers (Kapton, PPS, PTFE, etc.). Second, the adhesion and mechanical stability of the thermoelectric layer on textile: TE materials such as Bi₂Te₃/GeTe TEG are brittle, and thin films can crack under repeated bending. Here, typical microstructure of EB-PVD deposition may be paradoxically beneficial—a porous layer has better conformability under deformation and can accommodate stress through intercolumnar cracks without general delamination [14, 15]. Thus, an EB-PVD Bi₂Te₃/GeTe TEG film on a textile fiber could withstand repeated bending, unlike a dense which would continuously crack. Additionally, interposing a ductile buffer layer (e.g., a thin layer of Au or conductive polymer) between the fiber and the TE material could significantly improve the assembly's resilience.

Third, achieving sufficient generator output requires producing a large number of thermoelectric elements in series on an extended surface. EB-PVD could uniformly coat large textile surfaces, but the definition and connection of individual n/p elements require patterning. A suggested alternative in recent literature is the fabrication of individual n and p fibers (coaxially coated via PVD with different TE materials), which are then woven into a thermoelectric module-like structure. This modular strategy could be supported by EB-PVD by coating different types of yarns in a continuous configuration. Thus, a fully textile generator architecture can be achieved, where the coated yarns act as thermoelectric elements and electrical contacts can be realized by additional PVD metal layers applied to specific areas [16].

At the current stage [17], textile thermogenerators are still in the research phase, with several notable experimental demonstrations. For example, one group created a stretchable thermoelectric fabric using p- and n-type polymer nanocomposite yarns, achieving a power density of ~70 mW/m² at a temperature gradient of 44 K. Another group reported a 100% textile generator with printed organic elements, successfully generating several tens microwatts from the body-environment temperature difference. Compared to these, the inorganic approach via EB-PVD could offer superior performance per element (as inorganic materials have significantly higher Seebeck coefficients and power factors than conductive organic materials). However, the flexibility and ease of fabrication of organic solutions is undeniable. Most likely, a convergence of the two directions will be for example, layering necessary: nanostructured inorganic material onto textile via EB-PVD, then integrating it into a flexible polymer matrix for protection and reliability. Such a hybrid concept could combine the advantages of both worlds, enabling highefficiency textile thermogenerators that are also durable in real-world use [17].

Although no published reports currently exist on textile thermogenerators fully realized via EB-PVD, the fundamental elements of the technology indicate high potential for this application. EB-PVD can deposit established thermoelectric materials in unconventional forms and on non-standard substrates [17].

The remaining challenges—adhesion to fibers, thermal compatibility, and large-scale integration—can be addressed through process engineering (low-temperature deposition, use of buffer layers, segmented deposition patterns). If these issues are resolved, EB-PVD could play a central role in the fabrication of the next generation of thermoactive textiles, capable of generating electricity from heat, increasing the autonomy wearable electronic devices, contributing to the realization of energy selfsustaining wearable systems. Electron beam physical vapor deposition (EB-PVD) offers key advantages over sputtering or chemical deposition methods for fabricating flexible thermoelectric generators on polymeric or textile substrates. It achieves significantly higher deposition rates and yields high-purity films with precise thickness control, while imparting minimal thermal load on the substrate. These features enable the growth of thicker, well-adhered thermoelectric coatings on heat-sensitive flexible substrates without degradation [18].

CONCLUSIONS

The Electron Beam Physical Vapor Deposition (EB-PVD) method has established itself as a process for obtaining highwellperformance thin films, already recognized in demanding applications (thermal protection for turbines, optical layers, hard coatings, etc.). The present analysis highlighted the extension of this technology toward the field of flexible textile materials, a challenging area due to the delicate nature of the substrates. Recent studies demonstrate the feasibility metallizing textiles by EB-PVD in order to confer functional properties - especially

electrical conductivity and antibacterial activity. Cotton and other fiber textiles have been successfully coated with metals such as Cu or Ag, resulting in conductive textile materials that retain their flexibility and basic characteristics. It has been observed that substrate preparation (cleaning, smoothing, possible preliminary treatments essential for ensuring a polymers) is continuous film on the surface of the fibers. Metallic films deposited by EB-PVD exhibit very good adhesion and uniformity, translating into increased durability of the properties (low resistivity maintained after mechanical stresses from washing/abrasion). Moreover, the use of metals with biocidal properties (Ag, Cu) opens the path to the realization of antibacterial or antifungal textiles without the need for complex chemical treatments – a simple nanometric layer deposited in vacuum can confer the material with persistent antibacterial activity.

With textile regard to thermogenerators, these represent emerging application where EB-PVD could bring significant contributions. It has already been demonstrated that PVD processes are compatible with the fabrication of flexible thermoelectric generators on polymer films, including techniques derived from EB-PVD for the rapid deposition of active materials (Bi-Te, Sb-Te) [7]. The transposition of these technologies onto textile substrates could allow the direct integration of the energy generation function into clothing accessories. EB-PVD offers the advantage of obtaining crystalline-discontinuous thermoelectric materials which may be more resistant to deformation cycles, as well as the possibility to precisely control dosage and composition (necessary for optimizing doping in TE materials). However, before the practical implementation of textile thermo-generators manufactured through EB-PVD, several aspects must be resolved: (i) maintaining the integrity of textile fibers under vacuum and energetic bombardment process conditions, (ii) ensuring stable electrical contacts between thermoelectric elements on flexible support, and (iii) large-scale production of such structures in a cost-effective manner.

Overall, EB-PVD is emerging as a promising technology for functionalizing textiles at the surface level with unmatched control of the properties of the added layer. Whether it is about creating a textile material that generates electricity from body heat, or a textile bandage with a metallic antibacterial surface, EB-PVD offers the necessary tools to realize such concepts at the laboratory level, with the perspective of transitioning to industrial production once vacuum roll-to-roll processing technologies mature. The scientific community has begun to demonstrate the feasibility of these ideas. It remains to be seen to what extent EB-PVD will be efficiently integrated into the manufacturing flow of the textile industry, known for high volumes and low costs. In conclusion, EB-PVD represents a bridge between the field of thin films and that of flexible materials, and the intelligent exploitation of its benefits could lead to a new generation of smart textiles with integrated electronic and energy functions [7, 17].

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APPLICATION AND INNOVATION OF CLOUD SHOULDER ART IN MODERN BAG DESIGN

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APPLICATION AND INNOVATION OF CLOUD SHOULDER ART IN MODERN BAG DESIGN

ABSTRACT. Cloud Shoulder, as an important decorative element in traditional clothing of the Ming and Qing dynasties, holds rich cultural connotations and unique aesthetic value. This study explores the application and innovation of Cloud Shoulder art in modern bag design. Through an in-depth analysis of the historical background, design features, and cultural symbols of Cloud Shoulder, the study investigates its creative application in modern bag design. Specific cases of using Cloud Shoulder elements in contemporary bag designs are selected to analyze their design concepts, implementation methods, and market feedback, summarizing the application characteristics and innovative methods of Cloud Shoulder in modern design. Based on the research and analysis of Cloud Shoulder elements, modern bag design practices are conducted to explore innovative application methods of Cloud Shoulder in contemporary design. The results show that Cloud Shoulder art in modern bag design can not only inherit and promote traditional culture but also inject new inspiration and vitality into modern design, enhancing the aesthetic value and market competitiveness of bags.

KEYWORDS: cloud shoulder art, modern bag design, cultural inheritance, design innovation, aesthetic value

APLICAREA ȘI INOVAREA ARTEI GULERULUI ORNAMENTAL ÎN DESIGNUL GENȚILOR MODERNE

REZUMAT. Gulerul ornamental, ca element decorativ important în îmbrăcămintea tradițională din dinastiile Ming și Qing, deține conotații culturale bogate și o valoare estetică unică. Acest studiu explorează aplicarea și inovarea artei gulerului ornamental în designul genților moderne. Printr-o analiză aprofundată a contextului istoric, a caracteristicilor de design și a simbolurilor culturale ale gulerului ornamental, studiul investighează aplicarea sa creativă în designul genților moderne. Sunt selectate cazuri specifice de utilizare a elementelor gulerului ornamental în designul contemporan de genți pentru a analiza conceptele de design ale acestora, metodele de implementare și feedback-ul pieței, rezumând caracteristicile de aplicare și metodele inovatoare ale gulerului ornamental în designul modern. Pe baza cercetării și analizei elementelor gulerului ornamental, se dezvoltă practici moderne de design al genților pentru a explora metode inovatoare de aplicare a gulerului ornamental în designul contemporan. Rezultatele arată că arta gulerului ornamental în designul genților moderne poate nu doar să ducă mai departe și să promoveze cultura tradițională, dar și să aducă o nouă inspirație și vitalitate în designul modern, sporind valoarea estetică și competitivitatea pe piață a genților.

CUVINTE CHEIE: guler ornamental, designul genților moderne, moștenire culturală, inovație în design, valoare estetică

APPLICATION ET INNOVATION DE L'ART DU COL ORNEMENTAL DANS LA CONCEPTION DE SACS MODERNES

RÉSUMÉ. Le col ornemental, en tant qu'élément décoratif important dans les vêtements traditionnels des dynasties Ming et Qing, possède de riches connotations culturelles et une valeur esthétique unique. Cette étude explore l'application et l'innovation de l'art du col ornemental dans la conception de sacs modernes. À travers une analyse approfondie du contexte historique, des caractéristiques de conception et des symboles culturels du col ornemental, l'étude examine son application créative dans la conception de sacs modernes. Des cas spécifiques d'utilisation d'éléments du col ornemental dans les conceptions contemporaines de sacs sont sélectionnés pour analyser leurs concepts de conception, méthodes de mise en œuvre et retours du marché, résumant les caractéristiques d'application et les méthodes innovantes du col ornemental dans le design moderne. Sur la base de la recherche et de l'analyse des éléments du col ornemental, des pratiques de conception de sacs modernes sont menées pour explorer des méthodes d'application innovantes du col ornemental dans le design contemporain. Les résultats montrent que l'art du col ornemental dans la conception moderne de sacs peut non seulement faire avancer et promouvoir la culture traditionnelle, mais aussi apporter une nouvelle inspiration et vitalité dans le design moderne, améliorant la valeur esthétique et la compétitivité sur le marché des sacs.

MOTS CLÉS : art du col ornemental, conception de sacs modernes, héritage culturel, innovation en design, valeur esthétique

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INTRODUCTION

Cloud Shoulder represents a distinctive decorative tradition from Ming and Qing dynasty clothing, embodying sophisticated craftsmanship alongside profound cultural symbolism [1]. This ornamental element reflects the aesthetic philosophies and social values of its historical period while demonstrating exceptional artisanal skill [2]. Contemporary design practice increasingly recognizes the transformative potential of traditional cultural elements, with Cloud Shoulder emerging as a compelling case study for cultural preservation through design innovation [3].

The innovative integration of Cloud Shoulder art into contemporary bag design holds significant practical implications. Within the framework of cultural confidence, the modern transformation of traditional cultural elements has emerged as a vital pathway for design innovation. As one of the most representative decorative elements from the Ming and Qing periods, Cloud Shoulder offers distinctive formal language and abundant creative resources for modern bag design. Current bag markets face severe homogenization challenges, while consumer demand increasingly favors products with depth personalized cultural and characteristics. The incorporation of Cloud Shoulder elements effectively enhances product differentiation and competitive advantages, while facilitating the living transmission of traditional culture through daily-use carriers.

This research employs a comprehensive methodology involving examination historical literature, academic papers, and design works to understand Cloud Shoulder's origins and evolution, combined with case study analysis of contemporary applications in modern bag design. The study investigates design concepts, implementation approaches, responses and market to establish methodological frameworks for contemporary designers. Through creative practice and theoretical analysis, this research explores the form, color, pattern, and craftsmanship characteristics of Cloud Shoulder, discussing its unique charm in design expression, cultural inheritance, and market competitiveness while establishing foundations for cultural heritage integration in modern product development.

BACKGROUND RESEARCH

Historical and Cultural Background of Cloud Shoulder

Historically, Cloud Shoulder achieved prominence during the Ming and Qing dynasties, functioning as both aesthetic enhancement and social signifier Characterized by elaborate embroidery and complex patterning, these shawl-like accessories were primarily worn aristocratic women and wealthy households, serving as markers of status and cultural refinement. The design of Cloud Shoulder was often inspired by clouds in nature and traditional auspicious motifs, symbolizing beauty and harmony [5].

In the Ming and Qing periods, Cloud Shoulder was not just an aesthetic symbol but also held social and cultural significance. For instance, its complex patterns and fine craftsmanship often represented the wearer's status and identity, reflecting the hierarchical and aesthetic values of the time. Moreover, Cloud Shoulder's usage varied across different occasions and seasons, highlighting its importance in traditional rituals and cultural practices.

Application of Traditional Cloud Shoulder Elements in Modern Design

With the deepening of globalization and cultural exchange, the application of traditional cultural elements in modern design has gained increasing attention [6]. Designers are blending traditional elements with contemporary design concepts to create unique styles. This fusion not only helps in preserving and promoting traditional culture but also brings new vitality and creativity to modern design [7].

In contemporary Cloud Shoulder design applications, these elements are predominantly utilized in costume design for television dramas, such as "Empresses in the

Palace" and "Story of Yanxi Palace," where distinctive stylistic features have garnered widespread public appreciation. Domestic designers have conducted extensive theoretical and applied research on Cloud Shoulder design. For instance, Liang Hui'e and Liu Shui's study "The Meaning of Cloud Shoulder Form and Color and Its Innovative Application in Modern Women's Wear" explores the formal and chromatic significance of Cloud Shoulder, opening developmental spaces for modern fashion design through borrowing its structural forms and color schemes to explore novel design methodologies [8]. Shi Jianping and Wang Xuan's article "Application of Traditional Cloud Shoulder Costume Art and Its Decorative Aesthetic Significance" investigates traditional Cloud Shoulder forms and integrates traditional Cloud Shoulder art into modern garments such as gipao, evening gowns, and woolen sweaters, creating innovative clothing items that demonstrate Cloud Shoulder's artistic value and unique creative appeal in contemporary fashion [9]. Pan Jianhua considers the four-part Ruyi style and foursquare willow leaf style as typical forms, achieving fusion of ceremonial significance and decorative art through multi-layered structure and tailoring [10]. Liu Angi provides an overview of the artistic characteristics of Cloud Shoulder patterns, discussing application principles and specific practices of Cloud Shoulder patterns in modern product packaging design, aiming to provide systematic theoretical references for contemporary transformation of traditional patterns [11]. Li Jingtong develops a "pattern extraction symbolic transformation—cultural creative application" pathway for Qing dynasty Cloud Shoulder cultural creative development from a semiotic perspective, providing innovative approaches for the living heritage of Cloud Shoulder culture [12]. Li et al. conducted investigation, analysis, and synthesis of Qing dynasty Cloud Shoulder artifacts and related materials housed in the Soochow University Museum. By integrating interdisciplinary approaches from history, sociology, folklore, art studies, they examined and summarized the morphological evolution, characteristic classifications, and folkloric symbolism of "Ruyi Cloud" patterns in Cloud Shoulder designs [13]. While theoretical research on Cloud Shoulder elements in international academia remains relatively foreign designers' attention application of, and creative reconstruction of Chinese Cloud Shoulder in fashion design fields is quite prevalent. For example, in the film "Alice Through the Looking Glass," protagonist Alice wears Chinese-style costumes, with the most notable feature being the towering Cloud Shoulder design on both sides, demonstrating the gradually increasing popularity trend of Cloud Shoulder elements in modern fashion and cinema. Gucci's 2017 design combined Chinese Ming and Qing Cloud Shoulder elements with formal gowns, incorporating Chinese embroidery and dragon patterns in an East-West fusion. Burberry's "Cape Reimagined" exhibition toured multiple cities worldwide, where capes revealed traces of mixed-linked Ming and Qing Cloud Shoulder styles, with layered willow leaf-shaped Ming and Qing Cloud Shoulder elements fully expressing the layered style. Burberry combined feathers, knitwear, and lace elements with Ming and Qing Cloud Shoulder elements using deconstructive techniques, making the exhibits appear rich and full. Valentino's 2025 Spring/Summer Haute Couture collection employed the "four-square willow leaf style" Cloud Shoulder form, with color schemes extracted from traditional Cloud Shoulder, featuring varying numbers of willow shapes—eight, sixteen, eighteen arranged radially at the shoulders and waist, symbolizing a garden full of spring colors and eternal vitality. In summary, representative element of Chinese aesthetics, Cloud Shoulder is increasingly integrated into contemporary design practices to meet diversified aesthetic demands. Currently, domestic and international applications of Cloud Shoulder elements primarily concentrate in clothing, jewelry, packaging, and cultural creative product fields, with design focus largely remaining on borrowing its morphological characteristics, while in-depth extraction and application of its rich patterns remain relatively insufficient. Particularly in fashion bag design, the utilization of Cloud Shoulder patterns is even rarer. This reveals that research and application of Cloud Shoulder patterns in the bag design field harbors vast innovative space and developmental potential.

Precedents of Cloud Shoulder in Modern Design

The Cloud Shoulder, as a representative traditional element, has many successful applications in modern design. For example, some designers incorporate Cloud Shoulder patterns and structures into contemporary clothing, accessories, and bag designs. Through innovative design techniques and modern production processes, they breathe new life and fashion into Cloud Shoulder elements [14].

Specific cases include certain fashion brands that integrate Cloud Shoulder elements into their product lines. These brands use Cloud Shoulder curves and embroidered patterns in the design of shoulders or collars in clothing, retaining the essence of traditional elements while enhancing the simplicity and fashion sense of modern design. Additionally, some designers reinterpret and combine Cloud Shoulder patterns, applying them to modern bag designs to create products with unique styles and cultural connotations.

These precedents demonstrate that Cloud Shoulder elements can successfully bridge historical aesthetics with contemporary market demands, creating products that resonate with both cultural significance and modern functionality. This design approach meets consumers' dual demands for traditional culture and modern fashion, providing designers with abundant creative inspiration and possibilities.

Therefore, the historical and cultural background of Ming and Qing Cloud Shoulders, the application of traditional elements in modern design, and the precedents and innovations of Cloud Shoulder in modern design provide an important theoretical foundation and practical reference for this study. By reviewing and analyzing these literatures, this study will further explore the specific applications and innovative strategies

of Cloud Shoulder elements in modern bag design.

ANALYSIS OF CLOUD SHOULDER CHARACTERISTICS

As a significant decorative element in Ming and Qing dynasty garments, Cloud Shoulder's design characteristics are primarily manifested in its form, color, patterns, and craftsmanship. The structural styles of Cloud Shoulders are diverse, commonly including single-piece, layered, linked, and mixed types, with each style demonstrating distinct aesthetic features and craftsmanship levels. Scholars have categorized them into several common types based on their structural characteristics and compositional methods [15-16].

Form and Structure of Cloud Shoulder

Single-piece: This represents the earliest and most straightforward style of Cloud Shoulder, crafted from a single piece of fabric with simple yet elegant shapes that conform to the human body [17]. Despite its simple structure, the design often achieves sophistication and elegance through embroidery and patterns.

Layered: Constructed from multiple fabric layers stacked together, following the principle of bottom-to-top and large-to-small arrangement [18]. Layered Cloud Shoulders appear more substantial and luxurious, with more rhythmic color combinations, typically employing traditional five-color schemes for striking visual effects.

Linked: Compared to the overall stacking of layered styles, linked Cloud Shoulders feature more intricate structures. They are formed by connecting pre-cut independent shapes through beading, silk cords, or ingenious sewing techniques [19]. This structure often creates rich openwork effects, with each independent element requiring extremely delicate craftsmanship, and the combination demanding overall harmony and unity, presenting a transparent and dynamic aesthetic appeal.

Mixed: This style integrates multiple design elements and patterns together,

displaying rich variations and diversified effects [20]. Its design pursues abundant changes and diversified visual effects, innovatively combining different forms, patterns, and even craftsmanship techniques to satisfy more varied aesthetic demands, reflecting ancient artisans' active exploration and inclusiveness toward formal beauty.

Color and Patterns of Cloud Shoulder

The color design of "Cloud Shoulder" is rich in traditional Chinese aesthetic taste, typically using classic colors such as white, green, red, black, and yellow. Each color has specific meanings; for example, white represents purity, green symbolizes freshness, and red signifies passion. These color combinations not only produce a strong visual impact but also embody deep cultural connotations. Table 1 establishes a Cloud Shoulder color system based on traditional

Chinese Five Elements theory. In ancient China, there existed four great divine beings, also known as the Four Symbols (White Tiger, Azure Dragon, Black Tortoise, and Vermilion Bird), which originated from ancient stellar worship practices. These four mythical creatures were integrated with the Five Elements and directional orientations, represented distinct colors: eastern azure symbolizing Wood, western white representing Metal, southern vermilion denoting Fire, northern black signifying Water, and central yellow embodying Earth, each with corresponding symbolic associations. Ancient people expressed emotions and preferences through these colors while facilitating their application across different occasions. This color system only possesses profound cultural connotations but also provides scientific color coordination principles for contemporary bag design.

Table 1: Cloud Shoulder Colors and Their Meanings

Four Symbols	Yin-Yang and Five Elements	Traditional Five Colors	Modern Colors	Meaning
White Tiger (West)	Metal	White	White	Purity, Serenity
Azure Dragon (East)	Wood	Green	Blue	Freshness, Liveliness
Black Tortoise (North)	Water	Black	Black	Depth, Tranquility
Vermilion Bird (South)	Fire	Red	Red	Passion, Enthusiasm
Center	Earth	Yellow	Yellow	Harmony, Stability

In terms of patterns, Cloud Shoulder designs include floral patterns, mythical animals, and traditional folk stories, each representing people's wishes for a good life [21]. For example, plum blossoms in floral patterns represent noble character, and pomegranates symbolize fertility and

prosperity; dragons in mythical animal patterns symbolize power and wisdom, while phoenixes represent auspiciousness and nobility; traditional folk story patterns reflect historical tales and daily life scenes, rich in cultural symbolism. The types of Cloud Shoulder patterns are shown in Table 2.

Table 2: Types of Cloud Shoulder Patterns (Source: Beijing Institute of Fashion Technology Museum of Ethnic Costumes)

Pattern Type	Pattern Content	Pattern Image
Mythical Animal	The upper layer features deep red satin with flat embroidery, gold stitching, and seed stitching of butterflies and flowers.	
Mythical Animal	The visual center features an immortal sitting on a cloud releasing butterflies, with Wan symbols and domestic birds on the embroidery.	
Floral	Features stone green, green, and red colors, with embroidered butterflies, crickets, plum blossoms, chrysanthemums, bamboo, interlaced with willow leaves and semi-Ruyi patterns.	
Floral	White satin with embroidered birds and flowers using flat embroidery techniques, adorned with gold stitching in the form of a four-part Ruyi Cloud Shoulder.	
Floral	Willow leaf patterns, green satin with bird and flower patterns, golden toad on a lotus leaf, butterflies flying among the flowers.	
Traditional Folk Story	Depicts scenes of traditional weaving work, decorated with figures and courtyards, primarily using white satin.	

The Cultural Symbolism and Significance of Cloud Shoulder

In the Ming and Qing dynasties, Cloud Shoulder served as both an aesthetic symbol and a representation of ritual and status. Its complex patterns and fine craftsmanship signified the wearer's identity and social standing, reflecting the hierarchical views and aesthetic preferences of the era. During ceremonies such as weddings, Cloud Shoulder functioned as an important decoration,

expressing aspirations for marital bliss while showcasing noble status [22].

As a representative of traditional culture, Cloud Shoulder embodies profound aesthetic and cultural value. Beyond being mere clothing accessories, these intricate artworks demonstrate exceptional craftsmanship through their ingenious designs and sophisticated structural techniques. embroidery The unique characteristics of Ming and Qing Cloud Shoulder-from their distinctive forms to elaborate patterns-represent the profound heritage of Chinese traditional clothing culture, providing contemporary designers with abundant inspiration for promoting cultural inheritance and innovation in modern design.

CASE STUDIES OF CLOUD SHOULDER

Cloud Shoulder Elements in Scarf Design

Cloud Shoulder art has been widely and deeply applied in scarf design, especially in the integration into scarves, clothing, and jewelry, showcasing its unique aesthetic charm and artistic value. It is not only an aesthetic

application but also a transmission of traditional culture.

In scarf design, the color combinations and composition forms of Cloud Shoulder become sources of inspiration. The pattern designs mainly derive from figures, animals, plants, landscapes, etc.; by combining Cloud Shoulder patterns and colors with textile techniques, designers skillfully incorporate traditional Cloud Shoulder elements into scarf designs [23]. For instance, the EORILKS brand, dedicated to merging scarf design with Chinese culture, has a "Colorful Cloud Shoulder" series of scarves (see Figure 1). The inspiration comes from Cloud Shoulder art, extracting Ruyi cloud patterns and Cloud Shoulder tassel elements, depicting a series of elements such as chrysanthemums, tassels, butterflies, and orchids, and adopting a free composition form. This free arrangement emphasizes the direction and density of patterns and the rhythm of the design, providing a visual impact different from traditional designs (see Figure 2). In terms of color design, similar colors and complementary colors are used, with strong contrasts to stimulate the visual effects of consumers and promote consumption.



Figure 1. EORILKS "Colorful Cloud Shoulder" Series Scarf (Source: Official brand website)



Figure 2. EORILKS Design Pattern (Source: Official brand website)

Cloud Shoulder Elements in Clothing Design



Figure 3. Lafemme Cloud Shoulder Women's Dress (Source: Lafemme Official website)

In the 2019 Lafemme women's clothing series, a fashion show named "Forbidden City" was held to commemorate the 600th anniversary of the Forbidden City (see Figure 3). Part of the design drew inspiration from the Cloud Shoulder, using its overall shape in the silhouette and incorporating two tassels. The main color was chosen to be fungus purple, with gold accents, giving a romantic and elegant feel. The purple color also highlights the dignified and grand sense conveyed by the Cloud Shoulder. The fabric used mesh to create a four-part Ruyi pattern, with gold embroidery embellishing floral and plant motifs, perfectly blending the Cloud Shoulder with modern clothing, creating a collision of ancient and modern aesthetics.

Cloud Shoulder elements in clothing design bring a unique fashion language to the fashion industry. Designers skillfully use Cloud Shoulder designs on the shoulders or collars of garments, creating unique contours and a sense of line, making the clothing more three-

dimensional and artistic. This innovative design approach not only emphasizes comfort but also highlights the design layers of the clothing. With the rise of the "New Chinese Style" in fashion, many niche brands have vividly interpreted the integration of Cloud Shoulder art in modern clothing design.

For example, in the 2024 spring "Oriental Charm" New Chinese Functional Wind Sports Suit by YUEXI (see Figure 4), Cloud Shoulder art with an oriental freehand style is integrated into the sports suit, with neat and smooth shoulder lines paired with grey and white edge decorations. The development of Cloud Shoulder art in modern clothing design will become more diverse and creative, presenting a unique fashion atmosphere. TELL THE TRUTH Tai Zhen innovatively expresses Cloud Shoulder art with sequin tassels, featuring light purple ocean-themed embroidery on transparent white fabric, with sequin tassels around the edges. The unique use of colors and materials gives a cool and ethereal feel.



Figure 4. YUEXI 2024 Spring "Oriental Charm" New Chinese Functional Wind Sports Suit (Source: Official brand Little Red Book account)

Cloud Shoulder Elements in Jewelry Design

Cloud Shoulder elements in jewelry design bring a blend of classical and modern aesthetics to the pieces. Jewelry designers incorporate Cloud Shoulder patterns into necklaces, earrings, and other jewelry, breaking the conventions of traditional jewelry design and creating unique pieces with cultural depth [24]. This combination of traditional art elements in jewelry design not only adds decorative value but also imbues each piece with a narrative quality. Each piece of jewelry becomes a cultural canvas, allowing people to feel the historical and traditional charm.

In ancient times, the material of the Cloud Shoulder was a symbol of one's status. The "Record of the World" describes Cloud Shoulders and jewelry: "The collar decorations are of three types: the largest is made of white silk, draped over the shoulders, with embroidered flowers and birds on the chest and back, adorned with gold beads, jade, and

bells, making a sound when moving, called palace attire. The second is the Cloud Shoulder." This indicates that Cloud Shoulders were associated with jewelry and designed to reflect one's social rank.

In modern times, jewelry designs themed around Cloud Shoulders are also luxurious and textured. For example, Hong Kong's famous designer Wallace Chan designed a jewelry piece called "Fortune and Prosperity Cloud Shoulder" (see Figure 5). Utilizing the four-part Ruyi Cloud Shoulder style with symmetrical composition, the piece exudes a magnificent and grand feeling. It is adorned with different colors of jade, showcasing unparalleled luxury. The color scheme follows traditional Chinese Cloud Shoulder coloring principles, with white as the main color, complemented by green, purple, and orange. The secondary colors are distributed approximately at 25%, 15%, and 10%, creating a varied yet harmonious color palette.



Figure 5. Fortune and Prosperity Cloud Shoulder Jewelry (Source: Baidu Images)

APPLICATION OF CLOUD SHOULDER IN BAG DESIGN

As an important symbol of traditional culture, the artistic value of Cloud Shoulder has been fully realized in modern bag design. Designers integrate Cloud Shoulder elements into bag designs, preserving historical culture while giving new life to modern design. In this process, designers must consider how to retain the traditional aesthetic of Cloud Shoulder while innovating to make it vibrant in contemporary design [25].

During the design process, the rich colors, unique patterns, and exquisite

craftsmanship of Cloud Shoulder provide abundant inspiration for bag design. The aesthetic value of Cloud Shoulder art is reflected in its color diversity and pattern complexity. By recombining and innovating these elements, designers can retain the essence of traditional culture while meeting modern aesthetic demands. Using these traditional elements, designers products that possess both traditional charm modern fashion. enhancing attractiveness and market competitiveness of the products.

Incorporating Cloud Shoulder elements elevates product narratives while establishing

distinctive brand identities in competitive markets. In the context of the popular "Chinachic" culture, the elegance of Cloud Shoulder combined with the simplicity of modern design makes the bags not only practical but also stylish art pieces. This design approach meets consumers' demands for cultural heritage and aligns with their pursuit of fashion and individuality.

The application of Cloud Shoulder art in bag design is not merely a reproduction of traditional culture but an innovation. By reinterpreting Cloud Shoulder patterns, designers can retain its traditional aesthetic value while giving it new design language and expression. This innovation not only enhances the aesthetic value of the bags but also strengthens their market competitiveness, allowing brands to stand out in a homogeneous market.

The increased market competitiveness stems not only from design innovation but also from the rich cultural connotation [26]. The application of Cloud Shoulder elements gives the bags higher recognizability and cultural added value, attracting more consumer attention and favor. Through innovative applications of Cloud Shoulder elements, brands can establish unique images, increase market share, and boost sales. Additionally, the application of Cloud Shoulder art in design promotes the development of cultural creative products, expanding the product lines of brands and bringing broader commercial value.

From the above case studies, it is evident that many brands, through innovative designs, cleverly incorporate Cloud Shoulder elements into various parts of bags, such as straps and surface decorations. This not only preserves the essence of traditional elements but also infuses modern fashion sense, realizing the inheritance and promotion of traditional culture and providing abundant inspiration and methods for modern design.

Design and Development Process

This study selects Ruyi-style Cloud Shoulder as the primary design element based on the following considerations: First, through statistical analysis of Cloud Shoulder samples collected by institutions such as the Museum of Ethnic Costumes at Beijing Institute of Fashion Technology and the Palace Museum, Ruyi-style Cloud Shoulders were found to account for over half of all Cloud Shoulder styles during the Ming and Qing periods, demonstrating strong representativeness. Second, the curved structure of Ruyi-style Cloud Shoulders aligns more harmoniously with the formal language of contemporary bags, facilitating modernized transformative design. Finally, the Ruyi pattern itself symbolizes auspiciousness and fulfillment of wishes, corresponding to modern consumers' psychological expectations. Design development sketches (see Table 3).

Table 3: Design and Development Sketches (Source: Author's Own)

Design Stage	Design Sketches	Main Issues	Improvement Measures
First Draft		The design was not based on Cloud Shoulder form improvement, lacking innovation in patterns.	Strengthen formal variations and enhance pattern innovation.
Second Draft	正	Lacked integration with bag practicality, excessive external layers, unsuitable for mass production, complex manufacturing processes.	Simplify layered structure and enhance practical considerations.
Third Draft	正 担别数十种的数据 正 无规范 正 正 无规范 正 正 无规范 正 正 正 无规范 正 正 正 正 正 正 正 正 正 正 正 正 正 正 正 正 正 正 正	The second bag design was overly exaggerated and lacked practicality, patterns lacked coherence and were overly fragmented, with monotonous colors.	Optimize formal practicality, integrate pattern design, and enrich color combinations.
Fourth Draft		Pattern selection lacked coherence, color coordination lacked refinement, overall colors were overly monotonous.	Unify pattern styles and optimize color configuration schemes.
Final Draft		-	Addressed previous issues comprehensively to develop a final solution balancing functionality and aesthetics.

Color and Pattern Analysis

Color Selection and Application

Color variation is an important element of emotional expression in ethnic bags. Different colors exhibit different personalities, expressing various emotional tones such as rigidity, softness, warmth, and coolness. In the design of ethnic bags, Cloud Shoulder mainly uses bright, high-saturation colors to create a strong visual effect with contrasts.

The primary colors chosen are the "Five Colors" as the main colors, with "intermediate

colors" as supplements. The "Five Colors" are white, green, black, red, and yellow, representing the Chinese Five Elements of Metal, Wood, Water, Fire, and Earth. In the bags, this is reflected in green, red, yellow, white, and black, symbolizing that everything in the world comes from the Five Elements and belongs to the colors of all things [27]. The bags use this color scheme by dotting vibrant, lively reds on the calm black and green, creating a striking contrast. The use of high-purity colors achieves a varied and beautiful effect. As shown in Table 4, this illustrates the color design process.

Table 4: Color Design Process

Table 4. Color Design Frocess					
Design Stage	Design Content	Theoretical Basis	Application Strategy	Color Display	
Color Extraction	Extract the five-color system from traditional Cloud Shoulder: white, azure, black, red, yellow.	Based on Chinese Five Elements theory (Metal, Wood, Water, Fire, Earth).	Establish traditional color foundation palette.	White Water Typer (story) White Water Typer (story) Green Address On Typer (story) Black Conf. Throw'd Conf. Red Western and and Conf. France Conf. Story Yellow Conf. Throw'd Conf. Throw'd Standard Market Story Throw'd Standard Market Standard Throw'd Standard T	
Color Transformation	Adapt traditional colors to modern aesthetic needs.	Consider modern consumer color preferences and fashion trends.	Adjust color brightness and saturation.	R73 G127 B126 R101 G127 B128 R166 G199 B228 R38 G91 B145 R224 G194 B64 R243 G219 B113 R238 G233 B222 R201 G55 B41	
Color Configuration	Determine proportional relationships between primary, secondary, and accent colors.	Contrast and harmony color theory.	Primary tone: blue-azure color family. Accent colors: red- yellow color family.		
Specific Application	Apply color scheme to various parts of the bag.	Visual guidance and functional requirements.	Bag body: stable tones, patterns: vibrant colors, accessories: neutral colors.		

The bags employ this color strategy by incorporating vibrant and dynamic red accents

over a foundation of stable black and azure tones, creating striking contrasts through the

application of high-purity colors to achieve a varied and dynamic aesthetic appeal. This color scheme maintains the cultural connotations of traditional Cloud Shoulder while meeting the visual requirements of contemporary design.

Pattern Extraction and Innovation

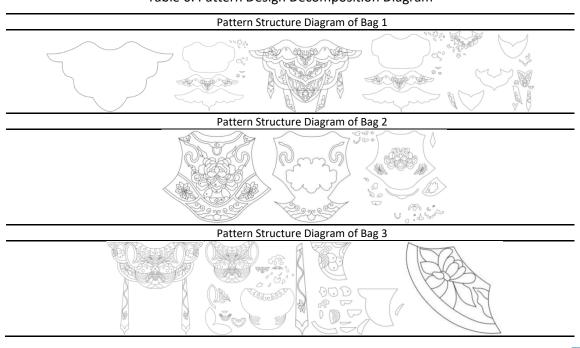
The application of patterns mainly includes insect and plant patterns. In ancient China, silkworm, cicada, and butterfly patterns were commonly used, with the butterfly pattern being the most representative. The butterfly pattern has auspicious meanings, representing fertility and prosperity, and a happy marriage. In the Ming and Qing dynasties, the legend of Liang

Zhu transforming into butterflies and the butterfly-loving flower pattern symbolizing the love between men and women were popular, as "butterfly" and "longevity" are homophones. the butterfly pattern often Therefore, symbolizes health and longevity. This is specifically reflected in the design of Bag 2. The plant patterns mainly use peony patterns, symbolizing prosperity, usually positioned at the center (Bag 3). They are paired with other flowers, where plum blossom patterns are used as decorations, connected by black lines to symbolize the continuation of offspring and rising success. Tables 5 and 6 illustrate the pattern design process.

Table 5: Pattern Extraction (Source: British Museum)



Table 6: Pattern Design Decomposition Diagram



Display and Evaluation of Developed Products

This study employs laser engraving and cutting technology as an alternative to traditional embroidery craftsmanship, primarily based on the following technical advantages. Comparative experiments revealed that laser cutting achieves pattern precision of ±0.1mm, representing a significant improvement over manual embroidery's ±2mm accuracy, enabling superior restoration of Cloud Shoulder patterns' intricate structural details. Regarding production efficiency, laser cutting requires approximately 3 minutes per pattern compared to traditional embroidery's 2-3-hour requirement, resulting in a 40-fold efficiency increase suitable for modern mass production demands. In terms of cost control, laser cutting reduces batch production costs by compared to conventional 60% techniques, with smooth post-cutting edges eliminating additional polishing procedures, further reducing time and labor expenses.

Laser cutting technology also demonstrates unique advantages in visual effects. Due to its high precision and minimal heat-affected zone characteristics, it ensures that colored materials maintain their original color purity during cutting and assembly processes, producing clear and smooth cutting edges particularly suitable for pattern designs requiring distinct color boundaries, making it ideal for expressing the rich layering of Cloud Shoulder patterns. Additionally, this technology provides designers with expanded creative possibilities, enabling precise cutting of complex geometric patterns and effectively extending the expressive forms of Cloud Shoulder elements in contemporary bag design [28]. The application of laser cutting technology not only addresses the limitations of traditional craftsmanship in modern production but also provides technological pathways for the contemporary transformation of Cloud Shoulder art. The finished products are displayed in Figure 6, with combined product presentations shown in Figure 7.



Figure 6. Final Product Display (Source: Author's Own)



Figure 7. Combination of Final Products Display (Source: Author's Own)

DISCUSSION

Challenges and Strategies in Design

In the process of applying Cloud Shoulder art to modern bag design, designers face challenges related to functionality and practicality. Although the traditional shapes of Cloud Shoulder are aesthetically pleasing, maintaining their complex structures in modern bag design may lead to practical deficiencies. Therefore, during the design process, it is necessary to simplify and generalize the main features of Cloud Shoulder, retaining its "multi-layered" design elements while ensuring the practicality and modernity of the bag.

The choice of materials and craftsmanship is another important challenge in design. To ensure the durability and practicality of the bag, top-layer cowhide with good breathability and sturdiness was selected to maintain the bag's quality in various Although environments. traditional embroidery can reflect the exquisite beauty of Cloud Shoulder, it is not suitable for modern mass production. To reduce production costs and enhance the modernity of the patterns, laser engraving and cutting techniques were adopted, making the design more youthful and aligned with contemporary aesthetics.

In terms of pattern design, Chinese culture has always valued the symbolic meaning of patterns, pursuing auspicious symbols such as "love," "happiness," and "health." Therefore, when designing Cloud Shoulder elements, these symbolic meanings need to be considered to enhance the cultural connotation and market appeal of the product, thereby improving the brand image.

The Value of Traditional Culture in Modern Design

As times progress and information becomes more widespread, people's design requirements are not limited to functionality but also emphasize individuality and aesthetic expression [29]. As an element of traditional culture, Cloud Shoulder art holds unique aesthetic value and deep cultural connotations, making it significantly valuable in modern design applications.

Cloud Shoulder is not merely a decorative piece but also carries rich cultural symbols and historical significance. Integrating Cloud Shoulder elements into modern design can evoke emotional resonance and cultural identity, promoting the inheritance and innovation of traditional culture. The traditional cultural elements conveyed through design works can enhance the depth and quality of design, providing viewers with a richer visual and emotional experience.

Incorporating Cloud Shoulder art into modern bag design facilitates traditional culture preservation while stimulating contemporary design innovation. By modernly interpreting traditional elements, designers can create works that possess both traditional charm and modern aesthetic appeal, achieving a perfect blend of tradition and modernity. This design innovation not only satisfies consumers' pursuit of uniqueness and cultural connotation but also enhances the market competitiveness and commercial value of the products.

In summary, the application of Cloud Shoulder art in modern bag design is not only a means of preserving traditional culture but also a form of innovation and enhancement in modern design. By continually exploring the application methods of traditional elements in modern design, designers can promote both design innovation and cultural inheritance, creating more works rich in creativity and cultural value.

CONCLUSION

This study explores the application and innovation of Cloud Shoulder art in modern bag design during the Ming and Qing dynasties. By deeply analyzing the historical background, design characteristics, and cultural symbols of Cloud Shoulder, the research investigates its re-creative application in modern design. This study combines specific cases to analyze the application characteristics and innovative methods of Cloud Shoulder in modern bag design and conducts creative practice in modern bag design, summarizing the innovative application methods of Cloud Shoulder in contemporary design.

As an important element of traditional Chinese clothing, Cloud Shoulder holds profound cultural connotations and unique aesthetic value. Its complex structure and exquisite patterns still possess strong visual appeal in modern design. **Findings** that Cloud Shoulder demonstrate reinterpretation successfully preserves cultural authenticity while generating innovative design solutions for contemporary markets. By incorporating Cloud Shoulder elements into design, designers can create modern bags with unique styles that meet the dual demands of consumers for cultural inheritance and fashion innovation.

The application of Cloud Shoulder elements in modern bag design not only enhances the aesthetic value of the bags but also increases their market competitiveness. The innovative application of Cloud Shoulder art in design makes the bags more recognizable and culturally valuable, thereby increasing the commercial value of the products. During the design process, by modernly interpreting Cloud Shoulder elements, designers can create works that possess both traditional charm and modern aesthetic appeal, achieving a perfect blend of tradition and modernity.

This study also emphasizes the importance of rationally applying traditional cultural elements in modern design. Through the research and application of Cloud Shoulder elements, designers can enrich the expression forms of modern bag design and promote the inheritance and innovation of traditional culture. In future design practices, it is essential to continue exploring the application of more traditional elements in modern design, promoting both design innovation and cultural inheritance.

The application and innovation of Cloud Shoulder art in modern bag design demonstrate the infinite possibilities of traditional culture in modern design, providing designers with abundant creative inspiration and methods. It is hoped that the findings of this study can offer valuable references for modern bag design, promoting the inheritance and innovation of traditional culture in modern design.

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EUROPEAN RESEARCH AREA

COTANCE NEWSLETTERS

Starting with January 2019, the COTANCE Council has issued a monthly *COTANCE Newsletter* with the purpose of **promoting an improved image of leather** to relevant decision makers and domestic stakeholders including Members of the European and National Parliament, Governmental authorities, Ministerial officers, Customers of the leather industry, Brands, Retail chains, Relevant NGOs, Designers, etc. The monthly newsletters present topics that tell the truth about a controversial aspect or a fact that is not well known by the general public to bring about a better understanding of leather and the European leather industry, as well as a positive predisposition to legislate in favor of the leather industry. The newsletters are available in seven languages at https://www.euroleather.com/leather/newsletter, and were also published in the 2019-2024 issues of *Leather and Footwear Journal*.



NEWS 4/2025



Step into Summer with Leather

The holiday vibe is here—Out of Office replies are popping up, and summer plans are in full swing. Whether you're heading out in June, July, August or even September, COTANCE is here with one sunny reminder before you pack your bags: your summer starts with **leather shoes**!

Why leather? Simple. Because nothing compares. As a natural material, leather adjusts to the shape of your feet, making every step feel just right. It allows your feet to breathe—especially important in hot weather—and offers the durability to handle everything from beach strolls to city adventures.

In this edition, we'll guide you through what to look for in quality leather footwear, from craftsmanship to comfort, so you can enjoy your holidays in style—and with happy feet.

Because leather isn't just a choice. It's the only one that walks the talk.

►► How to Choose the Perfect Leather Shoes This Summer?

We asked our members in Portugal, Spain, and France to share their expert tips on selecting the best leather shoes for the season. Here's what they have to say \P

Portugal – APIC

"For summer, we suggest a classic: leather sailing or boat shoes. Inspired by the maritime traditions of Portugal—where the Atlantic Ocean shapes not only our landscape but also our lifestyle—these shoes are a natural fit for summer adventures. Originally designed for life on deck, these shoes have become a summer staple thanks to their slip-resistant soles, soft leather uppers, and ease of wear. Whether you're walking by the beach or going out for a casual dinner, boat shoes made from quality leather will give you that effortless



summer look while keeping your feet cool and comfortable all day long. With the right pair of leather boat shoes, you carry a piece of Portugal with you—whether you're sailing or sipping rose at sunset".

Spain - ACEXPIEL / Ria Menorca

When it comes to summer leather shoes, the team at <u>RIA Menorca</u>—crafting footwear since 1947—knows the answer.

So what makes the perfect summer sandal?

According to **RIA Menorca**, there are 3 must-haves:

"It should be lightweight, breathable, and flexible. It should allow air circulation to keep feet cool and comfortable, and the leather should be soft enough to adapt to the shape of the foot without causing friction or discomfort".

Wondering how to spot quality leather in the shop? Here's their tip:

"Look for a natural, slightly irregular texture with a pleasant smell. It feels supple but firm to the touch, not plastic-like or overly shiny. When gently pressed, it should show slight wrinkles or

"pools," indicating flexibility and natural fibers".

As for materials, they recommend napa, goat, or soft calf leather—all thin, flexible, and ideal for hot days. Suede? A stylish choice too—if treated properly to resist stains and moisture.



And their personal summer tip?

"Choose leather footwear that is breathable, soft, comfortable, and easy to slip on and off. It should feel light and natural on your feet, making it perfect for summer days. A great example of this kind of shoe is the traditional Spanish "menorquina" sandal, which combines all these qualities with timeless style."

France - <u>Fédération Française de la Tannerie-Mégisserie</u> (FFTM)

"French women are always chic—no matter the weather or season—but they also prioritise comfort and foot health. And there's nothing better to combine both than leather shoes.

One classic example? Iconic leather ballerinas and espadrilles have become must-haves in French summer fashion. Light, elegant, and easy to wear, they're inspired by the charm of southern France—from seaside walks in Nice to relaxing on a café terrace in Provence—offering breathable comfort with effortless style. Made from soft, supple leather, they adjust naturally to the foot and absorb moisture—ideal for long summer days and warm evenings. Perfect for everyday strolls or evenings out, they're your go-to shoes for comfort and classic French style".



And one last thing —

Here are **3** essential shoe care tips by Chief Artisan Bar from The Purse Parlour, who is dedicated to preserving and restoring leather goods across Europe and beyond:

Choose leather over synthetics. Leather is durable, long-lasting, and can be beautifully restored when cared for properly.





- **Protect your shoes before the first wear.** A good leather protector will help shield your shoes from stains and moisture.
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Victory for Leather





July 17,2025



Victory for Leather: German Court Bans Misleading Use of "Apple Leather"

Cologne, 4 July 2025 – In a landmark ruling that defends consumer rights, the <u>Higher Regional</u> <u>Court of Cologne has officially prohibited</u> <u>Mina Merchandising GmbH</u>, owned by TV personality Martin Rütter, from marketing synthetic products using the misleading term apple "leather."

The decision, issued on July 4, 2025, follows a legal challenge initiated by the <u>Verband der Deutschen Lederindustrie (VDL)</u> - **COTANCE member,** after Mina Merchandising refused to comply with a warning over deceptive advertising of plastic-based dog collars labelled as apple "leather." The

court sided with VDL, confirming that the term "leather" may only be used when a product is made entirely or partially of animal hide.

The legal challenge, brought by the VDL, argued that labelling plastic-based products as apple "leather" misleads consumers and undermines the integrity of genuine leather. While a first-instance court rejected the claim, the Higher Regional Court overturned the decision on appeal, agreeing that the use of the term "apple leather" without actual leather content was deceptive and unlawful.

<u>6 U 51/25</u> 84 O 88/24 LG Köln



OBERLANDESGERICHT KÖLN IM NAMEN DES VOLKES URTEIL

-

für Recht erkannt:

Auf die Berufung des Antragstellers wird das am 19.02.2025 verkündete Urteil der 4. Kammer für Handelssachen des Landgerichts Köln – 84 O 88/24 – abgeändert und im Wege der einstweiligen Verfügung Folgendes angeordnet:

1. Der Antragsgegnerin wird untersagt, im geschäftlichen Verkehr in der Bundesrepublik Deutschland für Hundezubehör, insbesondere Hundehalsbänder, wie aus den nachfolgend einkopierten Screenshots ersichtlich unter Verwendung des Begriffs "Apfelleder" zu werben, wenn diese Waren weder vollständig noch teilweise aus Leder gefertigt sind:



"This is more than just a win for the leather industry—it's a win for consumers and truth in marketing. We are not against innovation, but we are against misleading labels that confuse buyers and devalue traditional, natural materials," - said Gustavo Gonzalez-Quijano, Secretary General of COTANCE.

This ruling sends a strong message to all brands and marketers across the EU and beyond: materials derived from fruit waste, plastic, or synthetic compounds cannot be marketed as "leather"—a protected term that implies natural origin and a specific production process. The use of vague or greenwashed terms like vegan "leather" or apple "leather" risks violating consumer protection laws by misleading the public into believing they are purchasing an authentic, sustainable product.



The initial court ruling in 2024 dismissed VDL's complaint, arguing that the color of the collar (blue) was enough to dispel confusion. However, on appeal, the Higher Regional Court rejected that logic and upheld the core argument: "leather" must mean leather. The judgment reaffirms that prefixes such as "apple," "rhubarb," or "cactus" do not justify misuse of the leather designation if no actual leather is present.

COTANCE applauds the persistent efforts of VDL in setting this legal precedent. As similar misleading practices grow across markets, this decision reinforces the urgent need for EU-wide rules protecting the authenticity of leather and ensuring a level playing field in product labeling.

A victory for leather is also a victory for consumers—and a strong signal to all companies profiting from the reputation and unmatched quality of genuine leather: the era of greenwashing is coming to an end.

Download the Press Release





You want to know more:

VDL | Website

Press Release | Euroleather.com

IULTCS NEWSLETTER



Edition 9, 2025

Welcome

This is the nineth edition of our scientific newsletter, dedicated to providing the latest updates on research, regulatory developments, technology, and standard methods in the leather industry.

NOTE: This newsletter is in English, Spanish and Portuguese. One version after the other. [LFJ Editor's note: For other language versions please visit www.iultcs.org].

In this issue, we feature an interview with Mr. João Carlos Graeff, a tanner, and Sales Manager for TANAC in Montenegro, RS, Brazil.

It is a great honor for IULTCS to have the collaboration of Mr. Graeff in a very important chemical for the leather manufacture: the extracts of Acacia used in the leather industry for both tannage and retannage of several types of leathers. The tannins from plants represent great value as being a renewable and biobased chemical that produce compostable leather.

We appreciate Mr. Graeff's collaboration with IULTCS Newsleather.

Please share your comments and suggestions to secretary@iultcs.org

Kind regards, Dr. Luis A. Zugno, editor

IULTCS INTERVIEW

Lifeline: João Carlos Graeff

Sales Manager of TANAC, Montenegro, Brazil

Joao holds a degree in Leather Chemistry from SENAI, Estancia Velha, Brazil, as well as an MBA in International Trade from FEEVALE, Novo Hamburgo, Brazil.

Joao has served as the Sales Manager at TANAC since 1991. He previously worked as a Leather Technician manager at tanneries in Brazil.



TANAC was created in 1948 and is considered the largest producer of Black Wattle trees in the world. This work is being done by thousands of families in Rio Grande do Sul and TANAC has planted more than 55 thousand hectares.

TANAC exports to over 70 countries, employs 1.000+ people practicing sustainability, and measures growth by economic and community impact.

www.tanac.com.br

IULTCS Question 1: Please describe briefly the history of Acacia Tannins in Brazil

Black Acacia (aka Wattle) is a species of tree (*Acacia mearnsii*), a leguminous tree native to Australia. Due to soil and climate characteristics that favor its development, this species adapted very well to the Southern region of Brazil, specifically in Rio Grande do Sul.

Historically, we have records of the first plantings in Brazil in 1918. Officially, the first commercial planting took place in 1930, when 30 kg of Black Acacia seeds were imported from Australia.

Black Acacia is cultivated mostly in Brazil, South Africa and India.

Historically worldwide, the use of Black Acacia trees may be older than we imagine, being even mentioned in the book of Exodus as a material used for the construction of the Ark of the Covenant (1).

The name "wattle" comes from an old Anglo-Saxon word referring to woven structures. Early English settlers in Australia used flexible branches and saplings—often from acacias—to create panels for their homes, known as "wattle and daub" construction (2). Because acacias were commonly used in this method, they became widely known as wattles.

In this interview we will use the term "Acacia Tannin" to describe the Black Acacia tannins and "Acacia" for the Black Acacia tree.



Figure 1: Acacia tree budding and full-size trees

IULTCS Question 2: How long is the growth cycle of Acacia trees? What are the uses of wood and bark?

In Brazil, Acacia trees mature in about seven years, making them ideal for reforestation. They enhance soil fertility by fixing nitrogen, unlike other species that deplete it. Acacia trees are one of the top three species used for reforestation in Brazil, along with Pinus and Eucalyptus.

The trees grow well in the Southern region of Brazil, particularly in Rio Grande do Sul, due to the suitable soil and climate conditions.

Composition of the Acacia trees:

- Wood: 90% The wood from Acacia trees is of high density and possesses long fibers, making it suitable for producing high quality paper and durable materials and generating high caloric energy
 - Bark: 10% The bark of Acacia trees contains between 30 to 40% tannin (dry bark basis)

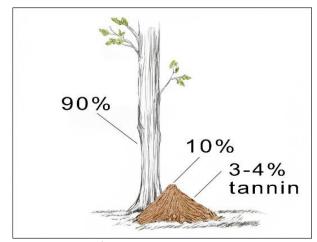


Figure 2: Diagram of the Acacia tree composition on dry basis

IULTCS Question 3: Mr. Graeff, please give us an overview of the Acacia Tannin production process

Here's a general overview of the process:

- 1. Harvesting & Preparation The bark of Acacia is removed mechanically from the trees, collected and dried to reduce moisture content.
- 2. Grinding & Extraction The dried bark is ground into smaller pieces and subjected to hot water extraction in counter current process to dissolve and concentrate the tannins.
- 3. Filtration & Concentration The concentrated liquid extract is filtered to remove solid impurities and then re-concentrated through evaporation.
- 4. Purification & Drying The tannin-rich solution is further purified and dried into powder (spray dried) or solid form for industrial use



Figure 3: Acacia concentrated tannin

IULTCS Question 4: Please give an overview of the Acacia Tannin as applied to the leather industry

Tannins are plant-based polyphenols present in many plants. Their main role in plants is to provide chemical defense against pests and insects.

Acacia Tannin is used in vegetable tanning because it bonds with proteins like collagen, stabilizing hides and turning them into leather.

Acacia tannin is often used to retan leather, especially after chrome tanning. It enhances filling, buffing, print retention, and product dispersion, giving leather a natural appearance.

The tanning process increasingly uses tannins from Acacia for its unique leather characteristics and eco-friendly benefits. These vegetable extracts are biodegradable and produce less waste and pollution. The choice of extracts depends on the desired final product qualities.

With the trend of slow fashion and sustainable brands prioritizing natural inputs for their reduced toxicity and environmental impact, Acacia extract has become more significant in this area.



Figure 4: Pile of vegetable tanned leather

IULTCS Question 5: Please describe which are the typical sizes of the full vegetable tanneries (is the number of tanneries growing or decreasing?)

Leather production has fluctuated in recent decades due to factors like fashion, global economic shifts, changing trends, raw material availability, and industry consolidation. Tanneries specializing in full vegetable-tanned leather are less affected by these changes, as they serve niche markets and focus on product quality.

As end consumers show interest in products produced with sustainable processes and reduced environmental impact, the use of vegetable extracts in the leather industry may become more common.

When comparing the sizes of tanneries, or rather the daily production in number of leathers, vegetable tanneries are generally smaller than those producing leathers for upholstery for example. Companies that tan with vegetable tannins range from family-run tanneries with monthly production in the dozens to leather sole companies with daily outputs of 1500 to 2000 hides. The market for leather goods such as saddlery and belts has seen significant growth in recent years, resulting in average tannery production reaching 500 to 1000 hides per day.

The global market for the vegetable tanning of sheep and goat skins is substantial. For instance, southern India produces large quantities of East India (EI) goat skins, which are tanned extensively using plant-based extracts.

IULTCS Question 6: What are the characteristics of different grades of Tannins from Acacia?

There are different products made with the same Acacia Tannins, and each chemical supplier has its own trade secret. The tannins can be modified before spray drying, and the most common chemical used is the sodium bisulfite as it plays a key role in modifying and extracting tannins from plant materials. When used in aqueous extraction processes, the sodium bisulfate helps break down complex tannin structures, making them more soluble and easier to isolate (3).

Specifically, it can:

- Enhance tannin yield by disrupting cell walls and aiding in the release of polyphenolic compounds
- Reduce tannin reactivity, which can be useful in applications like adhesives or leather tanning where controlled reactivity is important
 - Improve extract clarity

Once dried, Acacia Tannins can be blended with other syntans to modify their properties; for instance, this process can decrease reactivity, enhance fullness, or lighten the resulting color.

Main types of commercial Acacia Tannins:

- For pre-tanning of vegetable leathers

For the use of extracts for pre-tanning, modified tannins with lower astringency are sought to avoid surface tanning that hinders penetration and may lead to lower resistance to flower breakage.

- For sole leather

When choosing an extract for tanning soles and insoles leathers, the goal is to seek the highest tannins concentration and the best yield in relation to weight, thus the less modified tannins are the best option for these articles.

- For retanning

For the use of extracts for retanning leathers, tannins with greater dispersion and fillers are sought; thus, modified tannins for this purpose are the most suitable.

The main chemical and physical parameters that define a tannin product are:

Parameter	Comments
Color	Lovibond® scale using filters
% tannins	ISO 14088:2012 / EN ISO 14088.
% non-tannins	Quantitative analysis of tanning
% insoluble	agents by filter method ABNT NBR
% moisture	14818 NBR14818 Insumos - Tanante
pH 10% solution	

Table 1: Main parameters that define a dry tannin product

The quantity and choice of extract are directly linked to the desired article. When a technician seeks to perfect their article in the tannery and opts to use a vegetable extract in their production, it is because they aim to incorporate into their final product what their end customers are looking for.

In general, we can cite several characteristics that leather tanned with Acacia vegetable extract possesses, such as:

- Natural appearance of the leather
- Better burnishing or buffing
- Improved grain firmness and filling
- More uniform dispersion of dyes, syntans and fatliquour
- Biodegradability
- Processes with fewer chemicals

IULTCS Question 7: What will be the future of Acacia Tannins in 10 years? Will global production increase or decrease?

It is estimated that global tannin production capacity is between 160 to 190 thousand tons. Each tannin producing company has a strategy focusing on securing raw materials for tannin production. Growth is expected, contingent on reforestation and raw material availability. It is impossible to predict the future of the global tannin industry, and the old dream of making all the leather on the planet with tannins will be impossible unless the number of hides tanned reduces 1000 times.

Due to a growing demand for the use of vegetable tannins, not only in the leather industry but also in other market niches, TANAC has been working to promote the planting of Acacia in Rio Grande do Sul, either in its own areas or by encouraging planting in other areas, alongside rural families through its Forestry Promotion Program.

The planting of Acacia is very well received in Brazil, presenting several positive factors such as the 7-year cycle, which is considered short, the use of wood and bark, and its contribution to soil recovery.

In recent years, TANAC has increased both its planting area and forest promotion. This brings us more peace of mind for the near future, ensuring not only the necessary volumes but also the

quality standard, which is one of the main characteristics of the products delivered to our consumers.



Figure 5: Acacia seedlings (young plants grown from seeds)



Figure 6: Acacia forest

IULTCS Question 8: Compostability is one of the main sustainability requirements for leather. How do vegetable-tanned leathers perform in compostability?

When it comes to compostability, the use of vegetable extracts has the greatest advantage over other tanning methods. Compostability refers to the ability of a material to break down into natural, non-toxic components in a composting environment, leaving behind no harmful residues.

As an organic compound, Acacia Tannin is biodegradable, meaning it can be broken down by microorganisms in the soil. Additionally, once tannins decompose, they can enrich the soil with phenolic compounds that help improve soil structure, nutrient retention, and even act as a natural pest repellent.

IULTCS Question 9: Today what is the estimated percentage of Acacia Tannins used for leather (% vegetable full, % retanning)? What are the other uses of Acacia Tannins?

It is estimated that 65% of the Acacia Tannins are used for full Vegetable tannage and 35% for Retanning.

Polyphenols extracted from Acacia are powerful, plant-based ingredients used to create innovative, eco-friendly materials, including biopolymers for a wide range of applications. As natural, renewable, and fully biobased compounds, these polyphenols are gaining momentum in industries seeking sustainable alternatives.

While their use is expanding across sectors, Acacia tannins remain most widely used in the leather industry, where they play a key role in high-performance, environmentally conscious tanning processes.

Currently, Acacia extracts and their derived chemicals are used in various applications such as animal feed additives, agriculture, wood adhesives, coagulants for drinking and process water treatment, mining, and petrochemicals.

Due to its unique structure, plant extracts are anticipated to have additional applications in the future.

Tanning Method	Leather Type	Acacia Tannin Application %	Reference Weight Basis
Vegetable	Sole	40% to 45%	Limed weight
	Saddle	35% to 40%	Limed weight
	Belts	28% to 35%	Limed weight
	Metal Free	15% to 30 %	Shaved weight
Retan for	Shoe	7% to 15%	Shaved weight
Chrome and	Nappa	2% to 8 %	Shaved weight
Metal-Free	Upholstery	2% to 8%	Shaved weight

Table 2: Typical application dosage of Acacia Tannin

Note:

- These ranges indicate standard application levels for functional tanning or retanning
- Actual dosage may change based on the characteristics of the raw materials, targeted leather properties, and process conditions
 - Laboratory trials are suggested for formulation optimization

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- 2. https://worldwidewattle.com/schools/name.php
- 3. https://doi.org/10.4322/floram.2011.017



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IULTCS NEWSLETTER



Edition 10, 2025

Welcome

This is the tenth edition of our scientific newsletter, dedicated to providing the latest updates on research, regulatory developments, technology, and standard methods in the leather industry.

NOTE: This newsletter is in English, Spanish and Portuguese. One version after the other. [LFJ Editor's note: For other language versions please visit www.iultcs.org].

In this issue, we feature an interview with Mr. Thomas Strebost, a tanner, President and CEO of HELLER-LEDER in Hehlen, Germany in the fourth generation of the family-owned company.

It is a great honor for IULTCS to have the collaboration of Mr. Strebost, an alumnus of the Leather School in Reutlingen and worked as a tanner and later became CEO of HELLER-LEDER, modernizing the tannery, constructing two biogas plants, winning several local and international awards including the German Federal Cross of Merit. Mr. Strebost has been a leader in the leather industry through his roles as President of VDL (Association of the German Leather Industry) and participation on COTANCE, VGCT, ICT, FILK Leder Days and IULTCS.

We appreciate Mr. Strebost's collaboration with IULTCS Newsleather.

Please share your comments and suggestions to secretary@iultcs.org

Kind regards, Dr. Luis A. Zugno, editor

IULTCS INTERVIEW

Lifeline: Thomas Strebost

President and CEO of HELLER-LEDER GmbH & Co.KG of Hehlen, Germany

Thomas holds a degree in Leather Technology from Reutlingen, Germany. After his apprenticeship as a tanner and his military service time Thomas follows his father as President and CEO of HELLER-LEDER because his father died very early in the age of 51 in 1991.

Since then, he is the main shareholder of HELLER-LEDER, HELCOR-LEDER-TEC, and of 50% shares of Südleder a contract tanning company in South Germany.

Since 2004 he is the President of the German Tanning Association VDL.



HELLER-LEDER was founded in 1920 and is upheld and lived by owners and employees alike. The tannery produces cow (bull) leather from raw to finishing in Hehlen, Germany. HELLER-LEDER is recognized globally as a pioneer in environmental technologies with responsibility and respect for nature. HELLER-LEDER is an LWG Gold rated tannery and EMAS certified. www.heller-leder.com

IULTCS Question 1: Thomas, please give us an overview of the current leather industry in Germany. Are there future investment plans for Germany's leather industry?

In the moment we find the situation that there is more disinvesting than investments at the tannery side.

Nowadays HELLER-LEDER is the last automotive leather producing tannery located in Germany which is still working from raw hide to finishing in Germany.

If the general conditions won't change, I do not see that the German tanning industry will grow again.



Figure 1: HELLER-LEDER has been producing fine leathers since 1920



Figure 2: HELLER-LEDER is currently among the modern tanneries worldwide

IULTCS Question 2: What are today's biggest challenges for leather production at HELLER-LEDER?

The cost situation partly based on the General conditions (bureaucracy) and to find young talents are two big challenges.

Examples of bureaucracy are Energy uncertainty, carbon and decarbonization policies, multiple layers of legislation, chemical management (including REACH and ECHA), industrial hygiene, chemical waste, Circular Economy Act (2026), Corporate Sustainability Directive, regulatory complexity, etc.



Figure 3: Beamhouse drums (left) and unloading channels (right)

IULTCS Question 3: In your opinion what needs to be done to increase leather usage? Is it possible to still recover the volumes of leather we had in the past, or is it too late?

If the consumers and OEMs would understand that leather is the one of best and maybe the first example for circular economy the first step for more volume would be done.

A big opportunity could be if the consumer would be able to feel and see that leather is more natural than most of the alternative materials – therefore we have to come back to articles with less finish...

Another important point is that we must try to significantly improve animal welfare standards, even if we currently have little opportunity to exert influence.

The third point is that there is too much wrong information about leather in the world. If we could change this, it would help to increase sales.

IULTCS Question 4: HELLER-LEDER also processes the Modern Meadow substrate Innovera. Do you consider Innovera a complement or a threat to your leather production?

It is a complement because not everybody likes to buy or use leather, which has to be accepted. Together with Modern Meadow we are working on a very good sustainable alternative material.

IULTCS Question 5: HELLER-LEDER has been a global leader in leather production since 1920, winning many awards, including the Tannery of The Year 2011. How do you envision the company will be by 2035?

The next generation has started to work with us on the future, which is very important.

We've always tried to keep HELLER-LEDER modern, sustainable and successful with a certain growth but without plans to be the biggest...

This way we will continue in the future. As long people eat meat there should be tanneries around and we like to one of them.



Figure 4: Modern tanning and retanning drums at HELLER-LEDER

IULTCS Question 6: How are the regulatory issues (safety, environmental, sustainability, chemical management, etc.) affecting your leather business? How costly is it?

Like I mentioned before, bureaucracy and this is a part of it, is one of the biggest problems and cost drivers. It is the main reason why companies stop producing or change their production place.

In the moment our management team, with the next generation, is still fighting for better general conditions. We won't put our heads in the sand!

IULTCS Question 7: You have attended the iconic Reutlingen Leather School. Please share a few memories of your school time.

It was one of the best times in my life. The members of my class 89/91 are still in contact. Next year we plan to meet each other again.

It was a great help that the educational staff came out of the leather and chemical industry with a lot of practical knowledge.

We as students could learn and try in a small tannery – so we had the right combination between practical use and theoretical knowledge – we were able to try practically what we have learned theoretically – that opportunity was outstanding!

We all have learned what is important to know and what is less important.



Figure 5: Toggle and crust air drying

IULTCS Question 8: Today one of the biggest challenges is to replace chrome tanning, to produce compostable leather. Is HELLER-LEDER actively working to replace chrome totally or partially?

We were the first tannery which used the olive leave tannage (wet-green®). HELLER-LEDER always try to be in front when things are on their way to changing.

For our production we work over 90% Free of Chrome (FOC) with different tannages.



Figure 6: Olive leaves are a raw material for the wet-green® tannage and crust leather

IULTCS Question 9: On the last 50 years many of the German and Swiss chemical companies have left the leather industry, and this has affected drastically the R&D capabilities for the leather industry. In your opinion what needs to be done for future chemical needs in the leather industry?

Hopefully the remaining players will stay in the market and help our industry in case of future challenges.

The chemicals must be better and better in sustainability, in being as healthy as possible, as low costing as possible.... These are big challenges to work on.

As long there is a demand there will be R&D and chemical suppliers.

IULTCS Question 10: With the closing of the leather schools and many senior tanners retiring this is creating a void in technical expertise in the leather industry. How is HELLER-LEDER filling the technical expertise requirements for today and the future?

Since many years HELLER-LEDER is one of the tanneries with the most people in apprenticeship in the German tanning industry.

We also send as much interested employees as possible to the new German leather technician education.

We start with factory tour when kids are in the first school classes – the history shows the some of them become to be "Leather people" later.



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Title. Title (Centered, 12 pt. TNR font) should be short and informative. It should describe the contents fully but concisely without the use of abbreviations.

Authors. The complete, unabbreviated names should be given (Centered, 10 pt. TNR font), along with the affiliation (institution), city, country and email address (Centered, 9 pt. TNR font). The author to whom the correspondence should be addressed should be indicated, as well as email and full postal address.

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References. Must be numbered in the paper, and listed in the order in which they appear.

Diagrams, Figures and Photographs should be constructed so as to be easy to understand and should be named "Figures"; their titles should be given below the Figure itself. The figures should be placed immediately near (after or before) the reference that is being made to them in the text. Figures should be referred to by numbers, and not by the expressions "below" or "above". The number of figures should be kept to minimum (maximum 10 figures per paper).

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Formulas, Equations and Chemical Reactions should be numbered by Arabic numbers in round brackets, in order of appearance, and should be aligned left. The literal part of formulas should be in Italics. Formulas should be referred to by Arabic numbers in round brackets.

Nomenclature. Should be adequate and consistent throughout the paper, should conform as much as possible to the rules for Chemistry nomenclature. It is preferable to use the name of the substances instead of the chemical formulas in the text.

References should be numbered consecutively throughout the paper in order of citation in square brackets; the references should list recent literature also. Footnotes are not allowed. If the cited literature is in other language than English, the English translation of the title should be provided, followed by the original language in round brackets. Example: Handbook of Chemical Engineer (in Romanian), vol. 2, Technical Press, Bucharest, **1951**, 87.

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