Journal of Fiber Bioengineering and Informatics 18:1 (2025) 57–68
Cite as: S. Chu et al.
doi:10.3993/jfbim03052

Design Experiment on Easy-to-Wear Warm Boots for Wheelchair Users

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Abstract

To solve the problems of wheelchair users' shoes and boots in the aspects of convenience, warmth, and comfort in low-temperature environments and better meet their physiological and psychological needs, this paper proposes a structural design scheme of easy-to-wear and take-off warm boots based on a new type of warm wadding. At the same time, the fuzzy mathematics comprehensive evaluation method was used to select a new kind of flocculant with excellent thermal and wet comfort polyester fiber flocculant as the filling material for the follow-up warm boots. This paper has guiding significance and application value to the development and application of wheelchair users to put on and take off warm boots.

Keywords: Wheelchair users; Warm boots; Easy to put on; Heat retention property

1 Introduction

According to the World Health Organization (WHO) and the United Nations, about 131 million people in the global population need wheelchairs. Statistics from the China Disabled Persons' Federation show that as of 2020, more than 5 million people in China use wheelchairs every day, either permanently or temporarily [1]. For wheelchair users with poor lower limb activity, the blood circulation ability of the distal part of the lower limb is poor, the heat production is poor because of prolonged sitting, and the heat transfer is slow. Therefore, such people will have a greater demand for the convenience of wearing and removing lower-limb clothing products and the ability to keep warm from the cold.

Limited by physical function, mobility, dexterity, or endurance [2], wheelchair users have a high demand for the ease of wearing and removing clothing and footwear products. Wu Daiwei et al. [3] surveyed 58 test subjects who used wheelchairs due to lower limb disability. They found that most wheelchair users said it was difficult to put on and take off clothes when going to the toilet, bathing, and other activities. For the structural design of barrier-free shoes, almost all are designed into three-piece openings, and more Velcro is used to tighten [4]. These products

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Mar. 2025

solve the problem of wearing and removing them to a certain extent. However, the overall design function and beauty still lack innovation, and the winter use of warmth is not good, which cannot meet the basic psychological needs of wheelchair users in pursuit of beauty [5]. Therefore, it needs to be improved in many aspects.

According to the literature, an environment with an average temperature lower than 5 °C is defined as a low-temperature environment [6]. Exposure to low-temperature environments poses a serious challenge to human safety and health. The foot is located at the end of the lower limb, away from the heart, and has a relatively low blood supply, making it particularly vulnerable to cold stimulation. [7] Studies have shown that people feel uncomfortable, mostly because of foot discomfort. When the skin temperature of the foot is 28 $\sim$ 33 °C, the human body feels comfortable; when the skin temperature of the foot is 25 °C, the human body begins to feel a little cold; when the temperature is lower than 22 °C, the local blood circulation will be affected, making people feel uncomfortable [8]; when the temperature is lower than 21 °C, people will feel cold obviously, accompanied by discomfort and even pain [9]. When the foot temperature drops below 7 °C, there is a risk of frostbite [10]. As personal protective equipment used in cold environments, thermal boots can reduce the damage to the feet in cold environments. New floc filling materials such as hollow fiber, microfiber, aerogel, and composite thermal materials have become hot spots in the research and development of thermal clothing products. The new thermal materials will gradually lead the trend of the thermal materials market and develop toward thinner, more comfortable, and healthier while improving warmth.

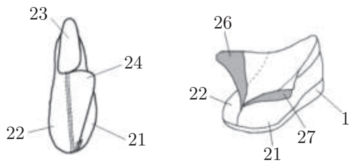
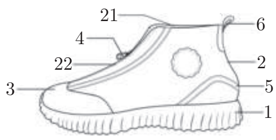
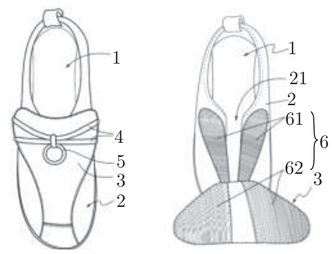
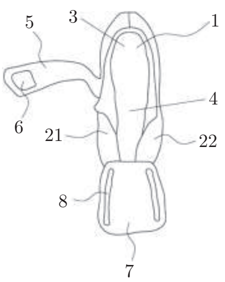
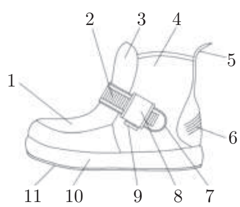
2 Method

2.1 Research Method of Structural Design Elements of Easy-to-Wear Thermal Boots

Domestic and foreign studies have shown that the convenience of wearing and removing clothing is the primary consideration in designing clothing for people with mobility difficulties [11]. The research based on the convenience of wearing and taking off shoes is mainly aimed at disabled people who cannot wear or take off clothes independently due to physical injury and their desire for independence. In the design, the details of shoes and boots should be considered, such as the choice of opening direction and fasteners, and the basic type of shoes and boots should be changed so that shoes and boots can be easily worn. Narrow the difference between the dress and appearance of people with mobility disabilities and normal people, and take care of their psychological state.

As shown in Table 1, most of the current studies on barrier-free boots start from the perspective of convenience of wearing and taking off. Most of them increase the boot cavity or open the boot upper to facilitate the access of the user's feet and use the buckle or binding to fix it. However, using the buckle leaves a gap between the two boot uppers and affects the thermal performance. The binding will be inconvenient to wear and take off, time-consuming, and laborious. It is necessary to develop a kind of easy-to-wear and take-off warm boots suitable for wheelchair users to solve the problem of the boots in the existing technology having a single structure, which is inconvenient to wear and take off. At the same time, long-term wearing will lead to fatigue and oppression because the shoe cavity space is too small.

Table 1: Research status of easy-to-wear shoes

Name	Style drawing	Design essentials
The utility model relates to middle-aged and elderly healthy-foot casual shoes that are easy to wear [12].		Pulling back the shoe cover to maximize the shoe mouth can make it effortless to put on and off.
A boot that is easy to put on [13].		The fastener replaces the shoelace hole near the mouth of the boot and is fixed through the winding of the shoelace and the fastener, which not only retains the beauty of the boot itself but is also convenient to wear, saving time.
A shoe for the disabled that is easy to put on [14].		Through the zipper connecting the opening seam, the shoes do not easily fall off, and the heel of the shoes. Setting the toe guard to avoid the problem of weak leg muscle strength and insufficient foot height caused by injury.
Wear and take off convenient shoes [15].		The upper is provided with an opening, and the tongue of the shoe is opened to form a fully open shoe; the tongue is also easy to re-fix to the upper and is easy to wear.
A shoe that is easy to put on and take off [16].		The left upper body and the right upper body are located at the instep to form an opening, which is communicated with the entrance. The left upper and the right upper on the periphery of the entrance are connected through a connecting belt, and the first connecting piece is fixed on the connecting belt.
The invention relates to warm and fleece children's boots that are easy to wear [17].		When the children's boots are used, set the card block and binding by inserting one end of the guide block along the inside of the card block through the set binding and adjusting the tightness through each card slot.

2.2 Experimental Instruments and Methods

The new floc materials were analyzed through a literature review, visits to clothing surface accessories exhibitions, and market research. Five new thermal flocs, each with a weight of 120 g/m^2, were selected as the experimental materials for this study. Considering economic and applicable factors, two types of traditional floc materials weighing 120 g/m^2 and sustainable thermal materials with low BPA content were selected as control materials. The flocs are numbered 1# through 7#. The basic specification parameters are shown in Table 2, and the image information of the flocs is shown in Fig. 1.

Table 2: Basic specifications of floc materials (Mean + STD)

Type	Batting number	Name	Fiber composition	Thickness (mm)		Actual square meter weight (g/m^2)	
				Mean	STD	Mean	STD
New Floc	1#	Aerogel insulation sheet	Aerogel + Polyester	6.40	0.56	125.47	0.44
	2#	Graphene flake	15% Graphene + Polyester	6.69	0.38	126.00	0.09
	3#	Microfine polyester fiber floc	Microfine Polyester	7.46	0.45	123.87	0.12
	4#	Heat fiber floc	30% Thermal fiber + 70% Polyester	6.27	0.45	125.50	0.27
	5#	Coffee carbon fiber floc	30% Coffee carbon + 70% Polyester	5.35	0.30	114.08	0.20
Traditional batting	6#	Sustainable thermal materials with low BPA content	Recycled polyester fiber	7.07	0.46	125.22	0.09
	7#	Down cotton	Hollow polyester fiber	8.97	0.47	119.80	0.16

Fig. 1: Small sample of floc materials

Thermal Performance Test: The warmth retention of a fabric is generally characterized by its thermal resistance- the higher the thermal resistance, the better the warmth retention of the fabric [14]. The thermal resistance of seven kinds of floc was tested according to the GB/T 11048-2018 standard, "Determination of Thermal and Wet Resistance under Steady State Condition of Physiological Comfort of Textiles (Evaporative Hot Plate Method)." The experimental instrument used was the M259B fabric thermal and wet resistance tester from SDL Atlas Company. Experimental conditions were set as follows: ambient temperature (20±0.1) °C, relative humidity (65±1)%, wind speed of 1 m/s, hot plate temperature (35±0.1)°C, and a sample size of 33 cm × 33 cm.

Permeability Test: The breathability of thermal wadding was tested using the YG461E breathability tester, following the standard GB/T 5453-1997 "Determination of Breathability of Textile Fabrics." Experimental conditions included a standard atmospheric temperature of 20.0±2.0°C and relative humidity of 65.0±4.0%.

Moisture Permeability Test: The floc's moisture resistance was tested per GB/T 11048-2018, and the moisture permeability was calculated. The lower the moisture permeability, the worse the fabric's ability to transmit moisture. The M259B fabric thermal and wet resistance tester was used for this experiment. Experimental conditions were set as follows: ambient temperature (20±0.1)°C, relative humidity (40±1)%, wind speed of 1 m/s, hot plate temperature (35±0.1)°C, and a sample size of 33 cm × 33 cm.

Compression Resilience Test: The compression resilience of floc is a key performance indicator for clothing wadding, usually expressed through the volume, compression rate, and recovery rate indices. The compression performance of the thermal wadding was tested according to the standard FZ/T 64003-2021 "Sprayed Cotton Wadding," Appendix A, which details the procedures for volume (specific volume) and compression resilience (compression rate, recovery rate) tests. Experimental conditions were set at a standard atmospheric temperature of 20.0±2.0°C and relative humidity of 65.0±4.0%.

3 Results

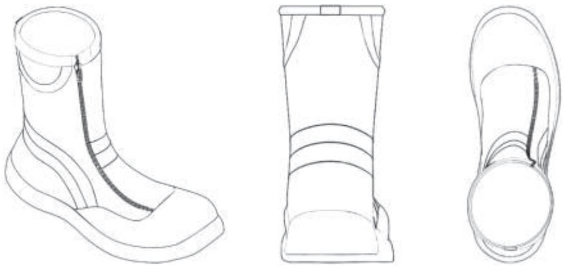
3.1 Structural Design Scheme

Scheme 1: The zipper of the easy-to-wear and take-off warm boots extends from the top of the boot tube to the bottom of the boot body and has a curved curvature, which can make the boot cavity open to the maximum extent to achieve the purpose of convenient wearing and taking off [18]. The elastic rope is set to correspond to the instep position by adjusting the elastic rope margin control and the shoe cavity space so as to expand the use range. The combination of the knitted thermal sleeve and the bootleg can keep the limbs above the bootleg warm. The boot body and boot tube are filled with thermal materials, and the knitted thermal sleeve flexible materials are added, which can adapt to the thermal requirements in various scenarios.

(a) (b) (c)

Fig. 2: Easy to wear warm boots structural design

Scheme 2: The zipper of easy-to-wear and take-off warm boots extends from the boot body to the top of the boot tube; both sides of the boot tube are provided with a magnetic lift, and the top of the boot tube is provided with a boot tube fastening assembly; The two ends of the magnetic handle are fixed connected with the top of the boot tube, the magnetic handle is a semicircular ring, the magnetic handle is provided with a magnetic buckle, and the boot tube is provided with a magnetic sheet corresponding to the magnetic buckle. The fastening rope holding ring of the boot tube fastening assembly is arranged at the top of the boot tube, and the spring press rebound device is exposed at one end of the fastening rope holding ring. One end of the fastening rope is rolled up and contracted in the spring press rebound device, and the other end of the fastening rope is fixed inside the other end of the fastening rope holding ring through the fastening rope ring. The design of the magnetic handle makes the wearing and taking off the warm boots simple and convenient, improving their convenience. The rope of the bootleg fastening assembly can be adjusted in length and fixed in different positions, which can be adapted to different body types.



(a) (b) (c)

Fig. 3: Easy to wear and take off warm boots structural design

3.2 Material Test Results and Analysis

3.2.1 Thermal Performance

Seven types of flocculants were evaluated for their thermal retention capabilities, and the results are presented in Table 3. According to the data, the flocculants can be ranked in terms of their warming properties as follows: 1# > 3# > 7# > 6# > 2# > 4# > 5#. The results show that 7# - composed of hollow polyester, demonstrated superior thermal performance compared to 6# - which consists of recycled polyester fibers with low BPA content. When comparing the new flocculants (1# through 5#) with the traditional flocculants (6# and 7#), adding new fibers to polyester results in enhanced thermal properties. Among the new flocculants, 1# and 3# exhibited the best performance, surpassing the traditional flocculants 6# and 7#, while 4# heating fiber flocs and 5# coffee carbon fiber flocculants showed the least improvement. Furthermore, the insulation performance of the flocculants is closely related to their volume and permeability, as these factors influence the air content and fluidity within the flocculants.

Table 3: Test results of insulation performance of flocculants (Mean + STD)

Batting number	Thermal resistance ($m^2 \cdot {}^\circ C/W$)	Heat transfer coefficient ($W/m^2 \cdot {}^\circ C$)	Crowe number (clo)	Mass converted thermal resistance ($clo \times 10^{-2}$)	STD
1#	0.470	2.13	3.03	2.41	0.017
2#	0.396	2.53	2.55	2.02	0.006
3#	0.464	2.16	2.99	2.41	0.005
4#	0.368	2.72	2.37	1.89	0.006
5#	0.299	3.34	1.93	1.69	0.007
6#	0.442	2.26	2.85	2.28	0.004
7#	0.446	2.24	2.88	2.40	0.009

3.2.2 Air and Moisture Permeability

Seven types of flocculants were evaluated for their air and moisture permeability, with the results shown in Fig. 4 and Fig. 5. The data reveal the following ranking of permeability values for the flocculants: 5# > 4# > 2# > 1# > 3# > 7# > 6#. Notably, 5# -comprising coffee carbon, demonstrated the highest permeability performance, whereas 6# and 7#-representing traditional flocculants exhibited the lowest permeability. The moisture permeability of the flocculants is ranked as follows: 5# > 4# > 2# > 7# >6# > 3# > 1. Here, 5# showed the best moisture permeability, while 1# had the worst moisture permeability performance.

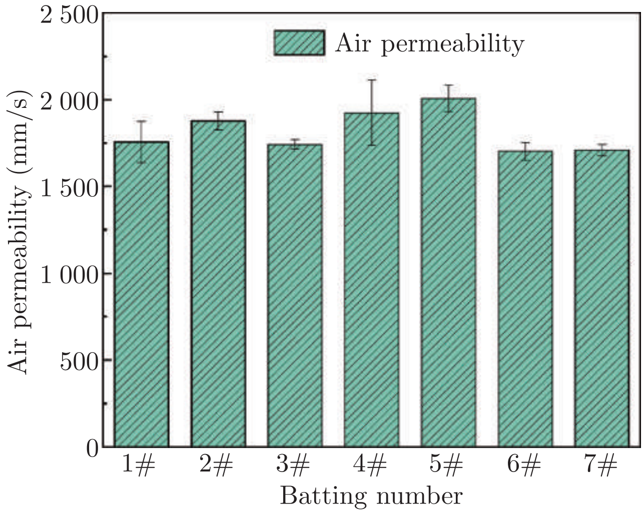


Fig. 4: Test results of permeability performance of floc

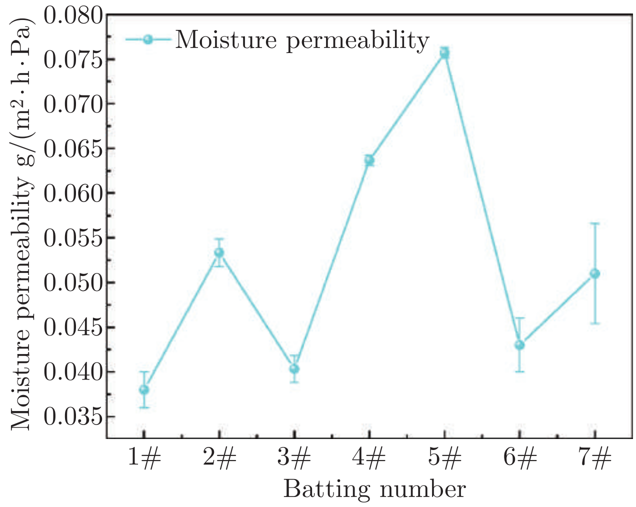


Fig. 5: Test results of moisture permeability of floc

3.2.3 Compressive Resilience

Table 4 ranks the seven types of polyester flocculants by size as follows: 1# > 4# = 7# > 6# > 3# > 2# > 5#. The volume of 1# floc is relatively large, indicating that the floc has the largest

Table 4: Test results of compression resilience of flocculants (Mean + STD)

Batting number	Filling capacity (cm^3/g)		Compressibility (%)		Resilience (%)	
	Mean	STD	Mean	STD	Mean	STD
1#	41	0.31	63	0.62	96	0.42
2#	36	0.31	63	0.41	96	0.52
3#	37	0.24	60	0.43	97	0.54
4#	40	0.37	62	0.33	98	0.52
5#	35	0.29	61	0.37	97	1.50
6#	39	0.21	60	0.49	97	1.71
7#	40	0.26	63	0.49	96	0.38

volume per unit mass, whereas 5# has the smallest volume.

A more stable bulk density in flocculants is more conducive to storing still air, reducing convective heat dissipation, and better thermal insulation performance. The seven flocculants' compression rate is 1# = 2# = 7# > 4# > 5# > 3# = 6#. The resilience rate is ranked as: 4# > 3# = 5# = 6# > 7# = 1# = 2#. These results indicate no significant difference in compression recovery performance between the new and traditional flocculants.

4 Discussion

4.1 Three-Dimensional Display of Easy-to-Wear Warm Boots

3D software is better than 2D software for product modeling [19]. Using Rhino, you can convert a two-dimensional curve set of a model into a three-dimensional design space. Due to the lack of experimental verification of the spring press rebound device of Scheme 2, Scheme 1 is finally selected for three-dimensional display after careful consideration of the thermal demand, convenience of wearing and removing, and protection of legs in the actual wearing scene. Figures 6 (a), (b), (c), and (d) show the left view, right view, top view, and front view of easy-to-put-on and take-off warm boots, respectively. This is suitable for wheelchair users. It is easy to wear and take off warm boots, including a boot tube, a boot body, and a boot sole; the boot tube and the top of the boot body are connected in one piece, and the boot sole and the bottom of the boot body is fixed connected. In the actual use process, the zipper on both sides separates the boot into two parts: the back and front. With the gradual opening of the zipper, the rear boot and the front boot are separated to the greatest extent, and the opening of the longitudinal boot gradually increases. Because the zipper extends to the bottom of the boot body, the transverse boot surface of the boot body will also be opened to a large part, which is convenient to wear and take off. The elastic rope in the shoe body corresponds to the instep position; pulling the elastic rope and using the buckle to fix it can achieve different foot types of people personalized wearing while pulling the elastic rope can match the zipper to achieve the purpose of more convenient wearing and taking off. When the warm boots are worn, the elastic rope can also be used as a decoration for the warm boots.

(a) (b) (c) (d)

Fig. 6: Three-dimensional display of easy-to-put-on thermal boots

4.2 Results and Analysis of Comprehensive Evaluation on the Comfort of Flocculants

More than a single index is required to evaluate flocculants' thermal and moisture comfort. Therefore, a fuzzy mathematical comprehensive evaluation method, which evaluates many related factors, was used to evaluate flocculants' comfort [20].

(1) Establishment of Factor Set U:

$$U = \{U_1, U_2, U_3, U_4, U_5, U_6\} \tag{1}$$

In the formula, U_1 through U_6 represent the flocculant's Crow value, air permeability, moisture permeability, volume, compression rate, and recovery rate, respectively.

(2) Establishment of Review Set V:

$$V = \{V_1, V_2, V_3, V_4, V_5, V_6, V_7\} \tag{2}$$

In this set, V_1 and V_7 correspond to flocculants 1# and 7#, respectively.

(3) Data Input and Matrix Formation:

The original data were input to obtain matrix X, as shown in Equation (3). The matrix elements, listed from top to bottom, include the Crowe value, air permeability, moisture permeability, volume, compression rate, and recovery rate. At the same time, the columns from left to right correspond to the fabric numbered 1# through 7#.

$$X = \begin{bmatrix} 3.03 & 2.55 & 2.99 & 2.37 & 1.93 & 2.85 & 2.88 \\ 1756.77 & 1878.09 & 1742.39 & 1923.31 & 2006.72 & 1703.01 & 1709.69 \\ 0.038 & 0.054 & 0.04 & 0.063 & 0.076 & 0.043 & 0.051 \\ 41 & 36 & 37 & 40 & 35 & 39 & 40 \\ 63 & 63 & 60 & 62 & 61 & 60 & 63 \\ 96 & 96 & 97 & 98 & 97 & 97 & 96 \end{bmatrix} \tag{3}$$

(4) Normalization and Evaluation:

The smaller the compression rate of the floc, the better the stability of its bulk density; the longer the thermal insulation performance, the larger the value of other factors, and the better the corresponding performance. After the range normalization of the original data, the evaluation matrix R was derived, as shown in Equation (4). Indicators for "the larger, the better" and "the smaller, the better" types are given in Equations (5) and (6), respectively, where X_{ij} represents the elements of matrix X, and $X_{i\max}$ and $X_{i\min}$ refer to the maximum and minimum values of elements in a row.

$$R = \begin{bmatrix} 1 & 0.564 & 0.964 & 0.400 & 0 & 0.836 & 0.864 \\ 0.177 & 0.576 & 0.130 & 0.725 & 1 & 0 & 0.022 \\ 0 & 0.421 & 0.053 & 0.658 & 1 & 0.132 & 0.342 \\ 1 & 0.167 & 0.333 & 0.833 & 0 & 0.667 & 0.833 \\ 0 & 0 & 1 & 0.333 & 0.667 & 1 & 0 \\ 0 & 0 & 0.500 & 1 & 0.500 & 0.500 & 0 \end{bmatrix} \tag{4}$$

$$r_{\text{larger}} = \frac{X_{ij} - X_{i\min}}{X_{i\max} - X_{i\min}} \tag{5}$$

$$r_{\text{smaller}} = \frac{X_{i\max} - X_{ij}}{X_{i\max} - X_{i\min}} \tag{6}$$

(5) Subjective Empowerment:

The weight coefficients $A(x)$ were obtained by soliciting the opinions of 10 experts in the textile and garment industries. These experts provided the weight proportions through a questionnaire, resulting in the subjective weighting coefficients shown in Table 4. The coefficients were calculated using Equation (7) to obtain the weighting coefficient set A:

$$a_i = \sum_{i=1}^{s} w_i x_i \tag{7}$$

$$A = \{0.342, 0.157, 0.1, 0.181, 0.085, 0.135\} \tag{8}$$

(6) Comprehensive Evaluation:

The comprehensive evaluation set is obtained by using the weighted average evaluation function:

$$B = A \cdot R = (0.551, 0.356, 0.568, 0.631, 0.381, 0.572, 0.484) \tag{9}$$

According to the comprehensive evaluation of fuzzy mathematics, the thermal and moisture comfort of the seven flocculants are ranked as follows: 4# > 6# > 3# > 1# > 7# > 5# > 2#. The 4# heating fiber flocculants exhibit the best thermal and moisture comfort. The comfort of 3# and 1# new flocculants is slightly lower but still superior to the traditional 6#, while the 2# new flocculant performs the least well in terms of comfort. Therefore, using the 4# new flocculant for follow-up applications involving easy-to-wear and removing thermal boots is recommended.

5 Conclusion

(1) The structural design idea of improving the convenience of wearing and taking off warm boots by freely adjusting the shoe cavity space is proposed. In the future, the structural design will be further improved according to the characteristics of human lower limbs, and the effective

Table 5: Expert weight statistics

i	U_1			U_2			U_3			U_4			U_5			U_6		
	x_i	N_i	w_i	x_i	N_i	w_i	x_i	N_i	w_i	x_i	N_i	w_i	x_i	N_i	w_i	x_i	N_i	w_i
1	0.06	1	0.1	0.1	2	0.2	0.15	1	0.1	0.35	1	0.1	0.15	1	0.1	0.19	1	0.1
2	0.37	1	0.1	0.21	1	0.1	0	1	0.1	0.21	1	0.1	0.08	1	0.1	0.13	2	0.2
3	0.3	2	0.2	0.15	1	0.1	0.1	4	0.4	0.18	1	0.1	0.13	1	0.1	0.14	2	0.2
4	0.35	2	0.2	0.08	1	0.1	0.17	1	0.1	0.15	3	0.3	0.1	2	0.2	0.15	1	0.1
5	0.65	1	0.1	0.2	2	0.2	0.03	1	0.1	0.20	1	0.1	0	1	0.1	0.25	1	0.1
6	0.4	1	0.1	0.05	1	0.1	0.14	1	0.1	0.11	1	0.1	0.02	1	0.1	0.05	1	0.1
7	0.2	1	0.1	0.32	1	0.1	0.11	1	0.1	0.06	1	0.1	0.04	1	0.1	0.07	1	0.1
8	0.44	1	0.1	0.16	1	0.1	–	–	–	0.25	1	0.1	0.12	1	0.1	0.1	1	0.1
9	–	–	–	–	–	–	–	–	–	–	–	–	0.11	1	0.1	–	–	–
Σ	–	10	1	–	10	1	–	10	1	–	10	1	–	10	1	–	10	1

Note: x_i—weight value; N_i—frequency; w_i—frequency

combination of knitted flexible materials and woven materials will be studied. This will provide an efficient and feasible design direction for the development of barrier-free shoes and enrich the categories of barrier-free clothing and apparel products.

(2) Heating fiber wadding demonstrated the highest wearing comfort. In comparison, down cotton, a traditional wadding with excellent performance was ranked lower than the heating fiber wadding, microfiber wadding, and aerogel thermal insulation wadding among the new materials. Recycled polyester wadding also showed lower comfort levels compared to heating fiber wadding. Therefore, heating fiber wadding is recommended as the filling material for developing thermal boots.

(3) The number of layers of footwear materials, the structural assembly, and the sanitary characteristics of specific materials greatly influence the heat and humidity exchange between the foot surface and the surrounding environment and the heat and humidity comfort of the shoe cavity. In the follow-up study, the optimal value of micro-environment temperature in the shoe cavity will be deeply explored from the aspects of multi-layer combination structure and relaxation amount of various thermal materials. At the same time, combined with the physiological structure of human lower limbs, the design of opening and closing methods that are easy to wear and take off is deeply studied to customize and meet the physiological and psychological needs of wheelchair users.

Acknowledgement

The authors gratefully acknowledge the financial support provided by Universal Apparel and Accessories Research and Practice, based on body and sporting features of disabled people (grant numbers 2019YFF0303304, ZXKY03190418).

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