Fibers and Polymers 2015, Vol.16, No.11, 2491-2496
DOI 10.1007/s12221-015-5363-1

ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

Analysis of Structure of Warp-knitted Spacer Fabric on Pressure Indices

Zhaoqun Du*, **Yuanxin Wu, Ming Li, and Linge He**

Key Laboratory of Textile Science & Technology, Ministry of Education, College of Textiles, Donghua University, Shanghai 201620, China

(Received May 12, 2015; Revised July 28, 2015; Accepted August 29, 2015)

Abstract: Spacer fabrics are widely used as mattress materials of bed and wheelchair. It is due to the fact that the special sandwich structure is effective in evenly dispersing pressure to improve pressure concentration, which prevents ulcer disease of long-term seated/lying people. However, there are few investigations on relationship between structure of spacer fabric and pressure behaviour. So, the main content dealt with in the paper was to adopt pressure pad system to measure pressure distribution behaviour of spacer fabric compressed by seated people, and pressure indices with average gradient integral, pressure peak, average pressure and contacting area were featured based on pressure nephogram. Pressure tests of varying surface stitch density, spacer filaments arrangement density and layers of spacer fabric were conducted. Experimental results showed that mattress without spacer fabric existed serious pressure concentration effect, while mattress with spacer fabric obviously improved hip pressure concentration effect. Pressure concentration effect could be well improved by increasing surface stitch density, spacer filament arrangement density and thickness. Moreover, it was a good method to produce mattress with good pressure property by combining reasonable layers of spacer fabrics to meet the same pressure-relief requirements.

Keywords: Spacer fabric, Pressure pad, Compression, Pressure distribution, Structure

Introduction

Spacer fabrics have been widely used as mattress and filling materials of bed and wheelchair in automobile, train and office furniture for light weight, good permeability and outstanding pressure distribution performance [1-3]. The key of these applications is the special sandwich structure of spacer fabric consisting of two separate surface fabrics as an upper layer and a bottom layer and one middle layer whose flexible filaments tightly link the bottom and upper surface layers. The special sandwich structure of spacer fabric is effective in evenly dispersing pressure and is excellent to avoid ulcer disease of long-term seated/lying people resulting from pressure concentration. The mechanism is due to the fact that when spacer fabric is compressed, spacer filaments are compressed to pull the surface fabric to make more surrounding filaments to be compressed so as to spread external force into larger areas with a gradual transition. Investigations on the pressure relief of warp-knitted spacer fabric are superior to sponge and wool carpets [4]. Moreover, cushioning property of spacer fabric shows that thicker spacer fabrics are effective for absorbing compression impact energy [5-8].

These application of spacer fabric as mattress depends on the structure and compression behaviour. Studies on structure of spacer fabric shows that spacer filament property, the number of spacer filaments per unit area and cross arrangement of spacer filaments have significant influence on compression pressure distribution. The compression resilience with cross arrangement of spacer filaments is better than that with a tilted upright arrangement; the bigger the bending stiffness of spacer filament, the better the compression recovery and the harder the spacer fabric feel [9-11]. Research on compression stress changes of spacer fabric under compression was focused on plate and spherical compression, which was used to obtain spherical compression stress and strain by integrating the theoretical formula according to the stress-strain curve of plate compression [12,13]. Some researchers analyzed the performance of static pressure relief on the basis of experimental and analytical methods to discuss spherical compression performance of spacer fabric, where Hertz contact theory was adopted to analyze the compression forces of the spacer fabric and various factors affecting compression performance, providing a good theoretical basis for the practical application of spacer fabrics [14]. These theoretical work makes solid basis to explain pressure relief mechanism. When spacer fabrics are compressed, spacer filament expands force area by pulling the surface structure, changes vertical downward pressure as a gradual transition to the side effects, so that the downward pressure is weakened and effectively reduces pressure concentration [15,16]. Currently, spacer fabric compression, especially spherical compression, focused on the surface of the fabric simulation analysis using finite element software. So, experimental verification is required to have a comparison with theoretical analysis results. Photogrammetry method was utilize for pressure measurement [17], and knitted fabric with silver plating was used to investigate tensile properties based on the relationship between stretching and electrical resistance in heartbeat monitor.

These methods are good to test surface tension of fabric, so it necessitates to measure the force normal to surface so as to have a comprehensive analysis of spacer fabric under compression. Wherein, pressure pad is a popular method to

*Corresponding author: duzq@dhu.edu.cn

measure normal pressure distribution of spacer fabric. Pressure distribution measurement system was utilized to test hip pressure distribution or sole pressure distribution so as to compare with a sponge on the pressure magnitude and distribution. Based on these methods, it could be well characterized that warp-knitted spacer fabric had better pressure dispersion than ordinary polyurethane foam. However, there are few investigations on relations between structure of spacer fabric and pressure indices [18]. Wherein, pressure relief test for six warp-knitted spacer fabrics showed good pressure relief effect compared with foam, and effect of different thickness and angle of spacer yarns on peak pressure and average pressure was significant. The above two pressure indices are not enough to analyze effect of structure of warp-knitted spacer fabric on pressure relief effect. Therefore, the paper focuses on the relationship between structure of spacer fabric and pressure distribution of spacer fabric as mattress. Then, pressure indices, including average gradient integral, pressure peak, contacting area and average pressure, were featured from the pressure nephogram so as to analyze effect of structure of spacer fabric on pressure behaviour.

Experimental

Samples and Preparation

Spacer fabrics were selected by varying structure and labeled as S1, S2, S3, S4, S5, S6 and S7, which were all produced by warp knitted technology, and the feeding forms of filaments of the upper surface and the bottom surface were selected as chain stitch and weft inlaid yarns. Spacer filaments were knitted into the chain stitch structure of the two surface so as to link the two surfaces into a whole fabric. In order to study effect of structure of spacer fabrics on pressure distribution, spacer fabrics S1 and S2 with different surface stitch density, and spacer fabrics S3 and S4 with different spacer filament arrangement density, and one-layer S1 and double-layers S5/S5 with equal thickness, and three-layers S6/S6/S6 and double-layers S7/S7 with equal thickness, and three-layers S4/S4/S4 and double-layers S4/S4, were selected. Specifications of spacer fabrics are listed in Table 1.

Pressure Testing System

Volunteers with weight varying from 45 kg to 80 kg were selected. They were healthy and had no history of musculoskeletal to participate in the test day. Pressure distribution tests of spacer fabric under seated volunteer were conducted according to Figure 1. The pressure testing system consisted of a Tekscan® pressure pad, a stool and a height-adjusting pad. Spacer fabric was put on the stool and the Tekscan® pressure pad was inserted between seated volunteer and spacer fabric. The stool was set on the height-adjusting pad so as to regulate the height of the stool to make volunteer knee's arch angle being perpendicular. For pressure testing, volunteers were required to let upper body upright and feet naturally fall to the ground for about 30 seconds. The pressure pad recorded pressure image every second and the average pressure image was calculated from the total 30 pressure images. The Tekscan pressure pad consisted of 42 rows×48 columns flexible film sensors to measure pressure, where each flexible film sensor's size was 10.16 mm×10.16 mm with thickness 0.1 mm and maximum pressure 33.48 kPa.

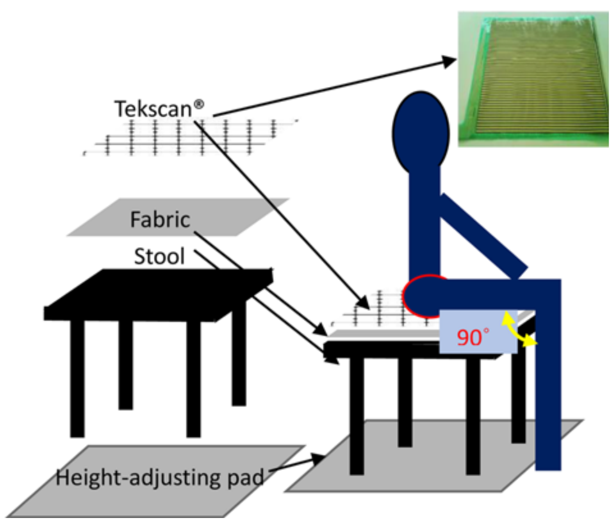


Figure 1. Schematic diagram of pressure testing system.

Table 1. Specifications of warp-knitted spacer fabrics

Samples		S1	S2	S3	S4	S5	S6	S7
Outer layers	Wale (5 cm)	35	45	45	42	35	36	40
	Course (5 cm)	30	26	13	13	30	29	28
	Structure	Locknit	Locknit	Hexagonal mesh	Hexagonal mesh	Locknit	Hexagonal mesh	Hexagonal mesh
Spacer filament	Thickness (mm)	20	20	8	8	10	6	9
	Diameter (mm)	0.20	0.20	0.23	0.23	0.17	0.22	0.23
	Number per (cm^2)	84	99	50	34	84	86	81
	View angle (^{o})	35	25	30	40	16	42	28

Table 2. Experimental design of pressure distribution test

Weight (kg)	Without spacer fabric and with spacer fabric as mattress				
45	None	S1	S2	S5/S5	
50	None	S4/S4	S4/S4/S4		
55	None	S3	S4		
80	None	S1	S2	S7/S7	S6/S6/S6

Test Process

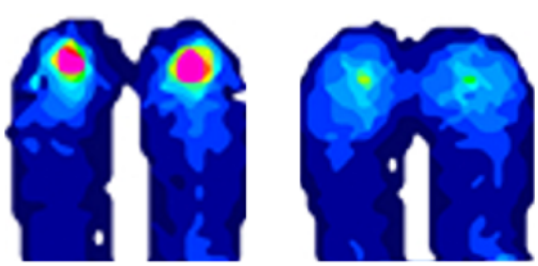
The corresponding experimental design method is listed in Table 2, which is used to analyze effect of structure of spacer fabric on pressure testing results, including spacer fabrics S1 and S2 with different surface stitch density for volunteer with weight 45 kg, and spacer fabrics S3 and S4 with different spacer filament arrangement density for volunteer with weight 55 kg, laminated spacer fabric on pressure property for one-layer S1 and double-layers S5/S5 with equal thickness 20 mm for volunteer with weight 45 kg, and three-layers S6/S6/S6 and double-layers S7/S7 with equal thickness 18 mm for volunteer with weight 80 kg, and three-layers S4/S4/S4 and double-layers S4/S4 of spacer fabric S4 for volunteer with weight 50 kg. Wherein, symbol "/" represents that the same spacer fabric is added. All experiments were conducted at temperature 25±3 °C and relative humidity 65±5 %.

Results and Discussion

Typical Pressure Nephograms

Typical pressure nephograms of pressure pad by seated volunteers with spacer fabric S1 and without spacer fabric as mattress are shown in Figure 2.

It was obvious from Figure 2 that there existed significant pressure concentration in red zones without spacer fabric. The pair of pressure maps showed that mattress with spacer fabric reduced pressure peak and extended contacting area so as to have a reasonable pressure distribution and to greatly improve the comfort. In order to have a good evaluation of pressure relief effect of spacer fabric, characteristic indices were featured from typical pressure nephograms, including pressure peak P_p, average pressure P_a, contacting area A_c and average gradient integral GI_a, where gradient integral was a differential gradient of pressure at any point, and average gradient integral was the average values of all points. These indices were utilized to analyze pressure relief effect of spacer fabrics.



(a) (b)

Figure 2. Pressure nephograms without (a) and with spacer fabric (b).

Effect of Structure on Pressure Relief Performance

Surface structure and spacer filaments affect tensile property of spacer fabric, which influence contacting area and pressure dispersion of spacer fabric under compression. So, spacer fabrics with varying surface stitch density and spacer filament arrangement density were chosen to study effect of structure of spacer fabric on pressure indices. Pressure tests for both spacer fabrics S1 and S2 with different surface stitch density for volunteer with weight 45 kg and spacer fabrics S3 and S4 with different spacer filament arrangement density for volunteer with weight 55 kg were conducted. Corresponding pressure nephograms are listed in Table 3.

It could be seen from Figures 3 and 4 that there existed red areas in pressure nephograms without spacer fabric, while there were no obvious red area in pressure nephograms with spacer fabrics. It shows that mattress with spacer fabric can obviously improve hip stress concentration effect.

For spacer fabrics S1 and S2 with different surface stitch density for volunteer with weight 45 kg in Figure 3, spacer filaments arrangement density of spacer fabric S1 is close to that of S2, while wale density is smaller and surface structure is relatively looser; meanwhile, spacer filament inclination angle of S1 is slightly smaller which leads to larger compression force at the same compression strain. So, spacer fabric S1 was more likely to be compressed against pressure dispersion, and pressure peak P_p, average pressure P_a and average gradient integral GI_a of spacer fabric S2 decreased by

Table 3. Pressure indices both with and without spacer fabrics under weights 45 kg and 55 kg

	None	S1	S2	None	S3	S4
Weight (kg)	45	45	45	55	55	55
P_p (kPa)	33.48	28.18	15.64	33.48	19.80	23.90
P_a (kPa)	5.505	5.272	4.675	7.752	5.832	5.758
A_c (dm^2)	6.297	8.079	8.366	6.104	6.975	7.009
GI_a (kPa)	1.455	1.369	1.190	1.332	1.118	1.117

(a) (b) (c)

Figure 3. Pressure nephograms without (a) and with spacer fabrics S1 (b) and S2 (c).

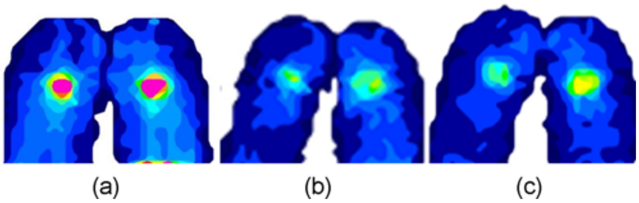


Figure 4. Pressure nephograms without (a) and with spacer fabrics S3 (b) and S4 (c).

44.5 % (equal to (28.18-15.64)/28.18), 11.3 % and 13.1 %, and contacting area A_c increased by 3.56 %. It demonstrates that spacer fabric S2 can effectively improve pressure concentration effect and is better than spacer S1.

For spacer fabrics S3 and S4 with different spacer filament arrangement density for volunteer with weight 55 kg in Figure 4, surface structure, thickness, spacer filament diameter are identical, while spacer filament arrangement density of spacer fabric S3 is 50 threads/cm^2 being 1.46 times of S4. It was obvious from the pressure nephograms that contacting area of spacer fabric S4 was 0.49 % slightly larger than that of S3, and average gradient integral and average pressure were 0.089 % and 1.27 % slightly less than that of S3. However, pressure peak of spacer fabric S4 increased by 20.7 %. It manifests that the influence of spacer filament density has significant effect on pressure peak, which is due to the fact that spacer filament inclination angles of S4 and S3 are 40^o and 30^o, and easily causes spacer fabric S4 to be compressed along one direction and to form an asymmetric pressure nephogram in right part of Figure 4. In addition, influences of spacer filament arrangement density on average pressure, average gradient integral and contacting area are small. In general, the higher the spacer filament density, the better the pressure-relief performance.

Effect of Laminated Spacer Fabrics on Pressure Performance

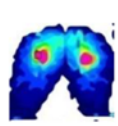
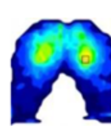
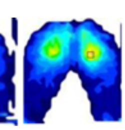
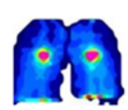
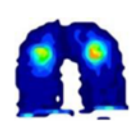
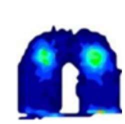
In order to analyze effect of laminated spacer fabrics on pressure property, pressure tests for one-layer S1 and double-layers S5/S5 with equal thickness 20 mm for volunteer with weight 45 kg, three-layers S6/S6/S6 and double-layers S7/S7 with equal thickness 18 mm for volunteer with weight 80 kg, and three-layers S4/S4/S4 and double-layers S4/S4 for volunteer with weight 50 kg, were conducted. Corresponding pressure nephograms are listed in Table 4.

Compared with pressure nephograms without spacer fabrics in Table 4, there existed difference for different laminated layers of spacer fabrics. Laminated spacer fabrics significantly decreased pressure concentration with red zones and affected pressure indices of spacer fabrics. Pressure peak, average pressure, contacting area and average gradient integral are improved obviously.

For single-layer S1 and double-layers S5/S5 with equal thickness 20 mm for volunteer with weight 45 kg, samples S1 and S5 have the same surface structure, while thicknesses of spacer fabrics S1 and S5 are 20 mm and 10 mm, respectively. Experimental results showed that contacting area A_c of double-layers S5/S5 was 8.441dm^2 larger than that of single-layer S1 being 8.079 dm^2, so pressure peak P_p, average pressure P_a, and average gradient integral GI_a of two layers S5/S5 being 24.29 kPa, 4.97 kPa and 1.251 kPa were all less than that one-layer S1 being 28.18 kPa, 5.27 kPa and 1.369. It indicates that double-layers of spacer fabric S5 has better pressure relief effect compared with one layer of spacer fabric S1.

For three-layers S6/S6/S6 and double-layers S7/S7 with equal thickness 18 mm for volunteer with weight 80 kg, spacer fabrics S6 and S7 have the same structure except for thicknesses of S6 and S7 being 6 mm and 9 mm. Compared with pressure indices without spacer fabrics, relative improving percentage of pressure peak, average pressure, contacting area and average gradient integral of both three layers S6/S6/S6 and two layers S7/S7 improved 20.6 %, 3.4 %, 12.7 %, 10.0 %, and 21.6 %, 6.1 %, 22.1 % and 11.0 %, respectively. It demonstrates that mattress with spacer fabrics significantly improve pressure comfort. In addition, pressure indices in Table 4 showed that pressure peak, average pressure and average gradient integral of three layers S6/S6/S6 were greater than those of two layers S7/S7. It manifests that pressure relief performance of two layers S7 is better than

Table 4. Pressure indices both with and without spacer fabrics

	None	S1	S5/S5	None	S6/S6/S6	S7/S7	None	S4/S4	S4/S4/S4
Weight (kg)	45	45	45	80	80	80	50	50	50
Pressure nephogram									
P_p (kPa)	33.48	28.18	24.29	33.48	26.59	26.26	33.48	20.80	18.32
P_a (kPa)	5.505	5.27	4.97	7.713	7.453	7.240	6.408	6.386	4.941
A_c (dm^2)	6.297	8.079	8.441	7.941	8.947	9.695	6.248	6.373	7.316
GI_a (kPa)	1.455	1.369	1.251	1.989	1.790	1.770	1.449	1.397	1.369

three-layers S6. It may be explained that they are closely warp-knitted structure organization and leads to greater compression stress during compression. The conclusions can be further proved by two-layers S4/S4 and three-layers S4/S4/S4 with weight 45 kg. Although the two combining methods adopted the same spacer fabric, contacting area increased and pressure peak, average pressure and average gradient integral all decreased for three-layers S4/S4/S4. Pressure-relief effect of three-layers S4/S4/S4 is better than that of two-layers S4/S4.

Subjective evaluation also proves the better pressure relief behaviour of double-layers S5/S5 compared with single-layer S1, and double-layers S7/S7 compared with three-layers S6/S6/S6 and three-layers S4/S4/S4 compared with two-layers S4/S4. Therefore, conclusion demonstrates that thickness of spacer fabric has a great influence on pressure relief performance. The greater the thickness, the better the pressure relief performance. However, the textile market can produce common fabric (fabric thickness ≤ 20 mm), and the weaving and setting process for producing spacer fabric more than 20 mm is complex and spacer fabric's quality is difficult to be controlled. Therefore, through combing sever layers of spacer fabrics, it is a good method to prepare mattress with good pressure property, because reasonable laminated spacer fabrics meet the same pressure-relief requirements.

Effect of Volunteers Weight on Spacer Fabric Pressure Performance

It is found that part of spacer fabrics have soft tactile sense under compression, while the other part of spacer fabric have stiff sense. Therefore, pressure test results may correlate with volunteers weight. In order to compare pressure-relief property of spacer fabric under volunteers with light and heavy weight, spacer fabrics S1 and S2 were selected to have pressure tests under volunteers' weights 45 kg and 80 kg, respectively. Average gradient integral GI_a for samples S1 and S2 are listed in Table 5. Furthermore, two derivative characteristic indices were featured based on average gradient integral so as to have a good evaluation of pressure relief effect, which included relative optimizing ratio of average gradient integral R and relative optimizing ratio of average gradient integral per weight of spacer fabric RW. Relative optimizing ratio of gradient integral R is.

$$R = \left(1 - \frac{\text{average gradient integral with spacer fabric}}{\text{average gradient integral without spacer fabric}}\right) \times 100$$

Then, R_{S1} and R_{S2} are relative optimizing ratio of average gradient integral of spacer fabrics S1 and S2, respectively. Relative optimizing ratio of average gradient integral per weight of spacer fabric RW is.

$$RW = \frac{R}{weight} \times 100\%$$

Then, RW_{S1} and RW_{S2} are relative optimizing ratio of average gradient integral per weight of spacer fabrics S1 and S2, respectively. GI_a-S1 and GI_a-S2 are average gradient integral of spacer fabrics S1 and S2, respectively. Symbol "None" in Table 5 represents average gradient integral without spacer fabric.

It could be seen from Table 5 that average gradient integral of spacer fabric S1 was 1.369 and 1.793 for light weight 45 kg and heavy weight 80 kg, and both were larger than that of spacer fabric S2 being 1.190 and 1.574, respectively. Relative optimizing ratios of average gradient integral of spacer fabric S1 for light weight 45 kg and heavy weight 80 kg were 5.91 % and 9.85 % smaller than that of spacer fabrics S2 being 18.21 % and 20.86 %. It indicates that spacer fabric S2 has better pressure relief property than spacer fabric S1. In addition, relative optimizing ratio of average gradient integral per weight of spacer fabrics S1 and S2 for light weight 45 kg were 0.13 % and 0.41 % larger than that for heavy weight 80 kg being 0.12 % and 0.26 %. It shows that relative optimizing ratio of average gradient integral is different for the same spacer fabric when applied by heavy volunteers and light volunteers. In order to explain pressure relief effect of spacer fabrics, spherical compression indices of spacer fabrics S1 and S2 featured from spherical compression force and distance curves are presented in Table 6.

It was obvious from Table 6 that compression work, compression work recovery ratio and linear degree of compression of spacer fabric S1 was similar to that of spacer

Table 5. Pressure indices both with and without spacer fabrics under weights 45 kg and 80 kg

Weight (kg)	None	GI_a -S1	RS1 (%)	RWS1	GI_a -S2	RS2 (%)	RWS2 (%)
45	1.455	1.369	5.91	0.13	1.190	18.21	0.41
80	1.989	1.793	9.85	0.12	1.574	20.86	0.26

Table 6. Compression indices of spacer fabrics S1 and S2

	Maximum compression force (N)	Compression work (J)	Compression work recovery ratio	Linear degree of compression
S1	17.4	0.100	0.760	0.765
S2	20.2	0.113	0.767	0.748

fabric S2, while maximum compression force of spacer fabric S2 under maximum compression strain 0.75 was 20.2 N larger than that of spacer fabric S1 being 17.4 N. It indicates that spacer fabrics S1 and S2 with different surface stitch density affects compression property and the corresponding pressure relief property is also different.

Conclusion

The paper adopted pressure pad system to measure pressure distribution of spacer fabric as mattress. Comparisons of typical pressure nephograms of seated volunteers on stool both without spacer fabric and with spacer fabric as mattress shows that the former exists seriously pressure concentration in red zones, while the latter obviously improve hip stress concentration effect. Then, four pressure indices were featured from pressure nephograms so as to investigate effect of structure of spacer fabric on pressure behaviour, including surface stitch density, spacer filament arrangement density and the number of laminated layers. Experimental results indicate that spacer fabric S2 with higher surface stitch density can effectively improve pressure concentration and is better than spacer fabric S1, spacer fabric S3 with higher spacer filament arrangement density effectively improves pressure-relief performance compared with spacer fabric S4, double-layers of spacer fabric S5 had better pressure relief effect compared with spacer fabric S1, pressure relief performance of two layers S7 is better than three-layers S6, and pressure-relief effect of three-layers S4/S4/S4 is better than that of two-layers S4/S4. Moreover, pressure test of average gradient integrals of spacer fabrics for light weight 45 kg and heavy weight 80 kg shows that pressure indices are different for the same spacer fabric when applied by heavy volunteers and light volunteers. Conclusion also demonstrates that pressure concentration effect is well improved by increasing surface stitch density, the spacer filament density and thickness of spacer fabric. Especially, it is a good method to prepare mattress with good pressure property to meet the same pressure-relief requirements just by laminating several layers and designing structure of spacer fabrics. It is helpful in solving difficult technology to produce very thick spacer fabric whose quality is difficult to be controlled. Moreover, for expanding analysis of combination of laminated layers of spacer fabrics and effect of weight of volunteer, much more spacer fabrics with varying structures should be designed according to good reducing-pressure concentration effect and have pressure property tests for a large number of volunteers with wide weights. The work on optimization of structure of spacer fabrics and relationship between objective pressure indices and subjective seating comfort level will be discussed in future.

Acknowledgement

This work is supported by Project (Grant 51203022, 11272086) supported by National Natural Science Foundation of China, and supported by the Fundamental Research Funds for the Central Universities (2232014A3-02) and supported by “DHU Distinguished Young Professor Program (B201307)”.

References

1. R. Bagherzadeh, M. Gorji, M. Latifi, P. Payvandy, and L. X. Kong, *Fiber. Polym.*, **13**, 529 (2012).
2. J. Yip and S. P. Ng, *J. Mater. Process. Technol.*, **209**, 58 (2009).
3. Y. P. Liu, H. Hu, H. R. Long, and L. Zhao, *Text. Res. J.*, **82**, 773 (2012).
4. X. Ye, H. Hu, and X. W. Feng, *J. Ind. Text.*, **37**, 213 (2008).
5. Y. P. Liu, H. Hu, L. Zhao, and H. R. Long, *Text. Res. J.*, **81**, 11 (2011).
6. M. Y. Wang, H. J. Cao, and K. Qian, *J. Eng. Fiber. Fabr.*, **9**, 1 (2014).
7. Z. Q. Du and H. Hu, *Text. Res. J.*, **82**, 1569 (2012).
8. X. H. Miao and M. Q. Ge, *Fibres Text. East. Eur.*, **16**, 90 (2008).
9. A. W. Vuure, J. A. Ivens, and I. Verpoest, *Compos. Pt. A-Appl. Sci. Manuf.*, **31**, 671 (2000).
10. J. Yip and S. P. Ng, *J. Mater. Process. Technol.*, **206**, 359 (2008).
11. D. M. Armakan and A. Roye, *Fiber. Polym.*, **10**, 116 (2009).
12. C. M. Wyk, *J. Text. Inst.,* **37**, 285 (1946).
13. Z. Q. Du and H. Hu, *Text. Res. J.*, **83**, 794 (2013).
14. J. Brandt, K. Drechsler, and F. J. Arendits, *Compos. Sci. Technol.*, **56**, 381 (1996).
15. F. Mokhtari, M. Shamshirsaz, M. Latifi, and M. Maroufi, *J. Eng. Fiber. Fabr.*, **6**, 23 (2011).
16. M. V. Hosur, M. Abdullah, and S. Jeelani, *Mater. Sci. Eng.*, **445**, 54 (2007).
17. S. P. Ng, W. Yu, and Y. Li, *Meas. Sci. Technol.*, **20**, 1 (2009).
18. X. Ye, R. Fangueiro, H. Hu, and M. D. Araújo, *J. Text. Inst.*, **98**, 337 (2009).