K.C. Lee[a], H.C. Tai[b], H.C. Chen[c]

[a] **Department of Textile Engineering, Chinese Culture University,** 11192 Taipei, Taiwan

[b] **Department of Physical Education, Chinese Culture University,** 11192 Taipei, Taiwan

[c] **Graduate Institute of Textile Engineering, Feng Chia University,** 40724 Taichung, Taiwan

Comfortability of the Bulletproof Vest: Quantitative Analysis by Heart Rate Variability

Abstract

A verification of regressive models based on artificial neural networks and multiple regres-This paper provides an effective quantitative analysis system and verifies it. The system of heart rate variability utilizes the reactions of the cardiovascular system for the duration of excitation. The paper analyses the qualitative records of those signals of physiological reactions formed, such as heart rate variability, variation of blood pressure and some effective indexes in the time and frequency domains. The variation of the autonomic nervous system (ANS) is the fastest and most effective adjusting mechanism against the internal and external environment of a human body. Further, the heart rate variability (HRV) has the properties of non-invasion and ease and is able to determine quantitatively and differentiate the activities of the sympathetic nervous and the parasympathetic nervous systems. Through the experimental results, the activities of the sympathetic nervous and the parasympathetic nervous systems can display precisely the physiological comfortability with objective data by using the analytical instrument of heart rate variability. The comfortability of the bulletproof vest can be improved substantially by employing functional textiles such as moisture-absorbing, quick-drying, waterproof and breathable fabrics.

Key words: *autonomic nervous system (ANS), quantitative analysis, heart rate variability (HRV), bulletproof vest, comfortability.*

Introduction

With the progression and variation of age, people have a higher demand for the comfortability of clothes. Many clothes equipped with protecting functionalities that emphasize the comfortability of clothes have been fabricated based on this tendency. Therefore, clothes with specific functionalities, like bulletproof vests, must still provide comfort. Comfort is judged mainly by the sense of touch and psychological factors. Describing the comfort of clothing is difficult because the user physiology and psychology as well as the external surroundings may differ.

The bulletproof vest is a functional clothing item. Its major capability is protecting life. Specialized materials must be used in bulletproof vests to enhance their performance; therefore, the bulletproof vest is heavy and uncomfortable. If a bulletproof vest is uncomfortable, it is inconvenient and reduces mobility. This not only reduces work efficiency, but also allows the wearers' lives to be threatened as they are in a dangerous situation [1]. Thus, the manufacturer must ensure that bulletproof vests are comfortable in order to improve the inclination of police officers to wear them.

Comfort factors are the user physiology factor, psychology factor, external surroundings and other factors. The human heart rate is mainly affected by the position of the body, exercise, emotion and body temperature. The sinoatrial node acts as a pacemaker by generating at regular intervals the electric impulses of the heartbeat. The frequency of the electric impulse is controlled by the autonomic nervous system (ANS) [2]. The key point of this study is to indicate those factors with a scientific instrument in an objective measurement method under a stable situation of physiology and psychology factors.

The heart rate variability (HRV) measurement of the physiological index was used to distinguish when the vest wearer was nervous, excited or tired from various reactions influenced by circumstances (sound, light, heat and cold) when engaging in works requiring physical strength and intelligence. In spiritual medical science, biofeedback techniques are utilized as monitoring tools to detect and expand the internal physiological messages [3, 4]. The HRV method indicates the intrinsic mental and physical states. However, HRV methods have never been used to assess the comfortability of bulletproof vests. This study is the first to measure bulletproof vest comfort using HRV methods to assess how different materials improve comfort in users such as police officers and army soldiers. This study showed that using Coolmax® not only improves the quality of the bulletproof vest but also enhances the comfortability when the user wears it.

Experimental

Materials

Two fabrics are used in the outer lining of bulletproof vests. One is a moisture-absorbing, quick-drying fabric. The other is a T/C 65/35 fabric used in bulletproof vests referred to as traditional vests in this study. The raw materials of moisture-absorbing, quick-drying fabric are 57% regular polyester and 43% Coolmax® fibre. This combination has proven effective for reducing skin temperature, lowering heart rate during exercise and maintaining hydration by offering excellent moisture management properties. Coolmax® has a special four-channel fibre structure that wicks moisture away from the skin into the moisture-absorbing outer fabrics. Besides, it also has a large surface area for faster evaporation. This mechanism enhances the evaporation of moisture from the fabric. The conformation is a plain structure, and the weaving densities in the warp and weft directions are 147 ends/inch with 75D/34f and 97 picks/inch with 150D/288f, respectively.

The T/C 65/35 fabric used in the outer lining of traditional bulletproof vests was compared with that used in the quick-drying bulletproof vest. The specifications of T/C 65/35 spun yarn in the warp and weft directions are Ne 44 S' (13.42 tex) and Ne 47S' (12.57 tex), respectively. This fabric construction was a plain structure, and the weaving densities in the warp and

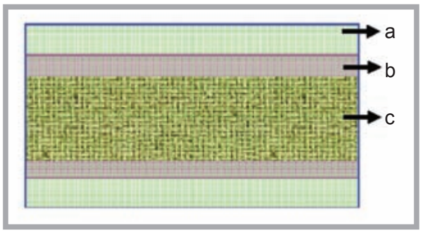

Figure 1. The sketch for the cross-section of bulletproof vest, a – outer lining, b – inner lining, c – bulletproof fabric.

weft directions were 140 ends/inch and 70 picks/inch, respectively.

There are also two kinds of fabric taken as the material for the inner lining. The fabrics used for the inner lining are the same polyester fabric with a high density weave and are coated without and with a PTFE (polytetrafluoroethylene) membrane, respectively. One is a non-breathable polyester fabric with a regular waterproof structure and a high weaving density in both directions. The weaving densities in the warp and weft directions of the lining of the non-breathable vest are 120 ends/inch and 90 picks/inch, respectively, and the fabric structure is plain. Another is the former fabric laminated with a Gore-Tex® membrane, which has a porous structure, referred to here as the breathable vest. Gore-tex® is a commercially available PTFE membrane, the porous membrane manufactured by W.L. Gore & Associates, Inc. ***Figure 1*** shows a cross-section of the bulletproof vest with the bulletproof fabric in the outer and inner linings. Basically, the inner lining keeps the bulletproof fabric dry and maintains the humidity of the fabric to prevent moisture damage.

The raw material used in the bulletproof vest is a woven fabric made of aromatic aramid (poly-paraphenylene terephthalamide) filaments that reach the IIIA level of bulletproof standard NIJ 0101.04. The commercial name of the Aromatic Aramid fibre is Kevlar®, which is manufactured by DuPont. The specification of Kevlar filaments is 1000 dtex. Kevlar fabric has a plain structure construction, and the weaving densities in the warp and weft directions are 25 ends/inch and 25 picks/inch, respectively.

Experimental procedures

Measurement of skin temperature

Static experiment: Different outer linings were compared in tests of users (hereafter "testers") wearing the bulletproof vest. Skin temperature was measured using an infrared thermal imaging camera (Telesis Digital Infrared Thermal System, Spectrum 9000MB) after static rest for 20 minutes.

Exercise experiment: The user ran on a treadmill (LDT-7850 HRC, Proteus) for 10 minutes with a 4-stage exercising mode while wearing the bulletproof vest. An infrared thermal imaging camera was then used to measure skin temperature. Each of the first 3 stages was 3 minutes long, and the 4th stage was 1 minute long. The running rates of each stage were 4.0, 6.0, 8.0 and 10.0 km/hr, and the gradients were set as 10°, 12°, 14° and 16°, respectively.

Measurement of heart rate variability

The "heart rate variability'', which is the variability between heartbeat intervals (RR intervals), is conventionally used to describe variations in both the instantaneous heart rate and RR intervals. In order to describe the oscillation in consecutive cardiac cycles, the literature reveals the use of other terms such as cycle length variability, heart period variability, RR variability and RR interval tachograph, which more appropriately emphasizes the fact that it is the interval between consecutive beats that is being analysed rather than the heart rate per second. However, these terms have not gained as wide an acceptance as HRV. Thus, the term HRV is used in this study [4-6]. The HRV has been recognized as the optimum method for evaluating the auto static experiment: in this test, the subject wore the bulletproof vest with different outer linings. The heart rate variability was measured after static rest for 20 minutes by using an Autonomic Nervous System Analyzer (ANSA, WeGene Technologies). The ANSA is a patented product of WeGene Technologies, Inc. in Taiwan. It provides a computerized data analysis of three cardiac rhythms: high frequency (HF, 0.15~0.4 Hz), low frequency (LF, 0.04~0.15 Hz) and very low frequency (VLF, <0.04 Hz) [4, 5, 7].

The VLF, LF and HF power components are usually measured in absolute values of power (ms2), but LF and HF may also be measured in normalized units [8, 9] that represent the relative value of each power component in proportion to the total power minus the VLF component. Representing LF and HF in n.u. emphasizes the controlled and balanced behaviour of the two branches of the autonomic nervous system. Moreover, normalization tends to minimize the effect on the values of the LF and HF components of changes in total power. Nevertheless, normalized units should always be quoted with absolute values of LF and HF power in order to describe the total distribution of power in the spectral components [4, 5].

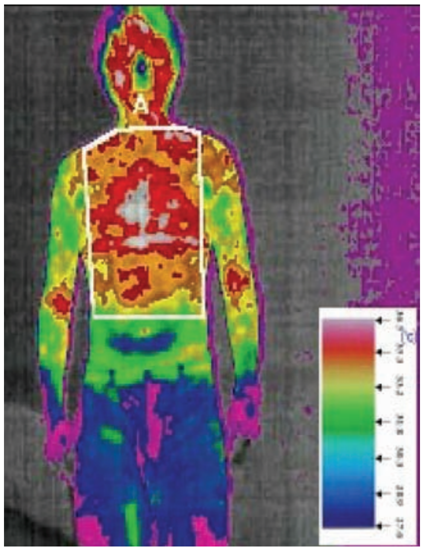

Figure 2. *Distribution of tester's skin temperature indicates tester wearing on a traditional bulletproof vest after exercise mode for 10 minutes. (Bulletproof level: NIJ IIIA, outer lining: T/C 65/35 woven fabric, inner lining: waterproof nylon fabric, bulletproof fabric: Aromatic Aramid Woven Fabric).*

The high frequency (HF) rhythm is associated with respiration whereas the low and the very low frequency (LF) rhythms are associated with both blood vessels and the vasomotor reflexes. Physiologists have discovered that the high frequency rhythm represents the function of the parasympathetic nerves, and the ratio of LF (low frequency) to HF (high frequency) represents the sympathetic nerve function. The autonomic nervous system (ANS), which is composed of sympathetic and parasympathetic nervous systems, affects many human organ functions. Autonomic nervous dysfunction may lead to many illnesses, such as heart disease, hypertension and sudden death [10, 11].

Exercise experiment: A subject wearing the bulletproof vest ran on a treadmill in a 4-stage exercise mode for 10 minutes. The heart rate variability was then measured. Each period of the first 3 stages was 3 minutes, and the 4th stage was 1 minute. The running rates of each stage were 4.0, 6.0, 8.0 and 10.0 km/hr at gradients of 10°, 12°, 14° and 16°, respectively.

Results and conclusion

Analysis of skin temperature

After 10 minutes in the 4-stage exercise mode, an infrared thermal imaging camera was used to measure the highest, lowest and average skin temperatures of the subject. ***Figures 2*** and ***3*** show the results. ***Figure 2*** indicates the distribution of skin temperature in subjects wearing the traditional bulletproof vest. ***Figure 3*** shows the highest, lowest and mean skin temperatures in the users after the exercise mode without the bulletproof vest, with the quick-drying vest and with the traditional vest. The material of outer lining for quickly-dry vest is moisture-absorbing and quickly-dry fabric and the traditional one is T/C 65/35 woven fabric. The exercise analysis indicated that the lowest temperature was about 32.34 °C without the bulletproof vest, and this condition was considered the most comfortable state in this study. The exercise analysis indicated that the highest temperature was 36.29 °C when wearing a traditional vest and this condition was defined as the most uncomfortable state in this study. When wearing the quick-drying bulletproof vest, the distribution of the highest, lowest and mean skin temperatures of the user was located between the most comfortable and the most uncomfortable states. Hence, the results of the distributions for skin temperature prove that the functional textile, moisture-absorbing and quick-drying fabrics used in the outer lining of the bulletproof vest really improve its wearing comfort and are effective for wicking moisture away from the body.

Analyses of heart rate variability (HRV)

Analyses of the activity of autonomic nervous system (ANS)

Figure 4 shows the analyses of heart rate variability in a subject wearing the bulletproof vest and also shows the autonomic nerve (AAN) activity in static mode. Compared with subjects wearing a traditional bulletproof vest, those wearing no bulletproof vest, a moisture-absorbing vest and a quick-drying bulletproof vest revealed similar activities of autonomic nerves (AAN), and the variation in activity was statistically significant.

Figure 5 indicates the activities of autonomic nerves (AAN) in exercise mode. The sequences of activities of autonomic nerves (AAN) in exercise mode were without vest > quick-drying vest > traditional vest. The autonomic nervous system includes both sympathetic and parasympathetic nervous systems. Thus, the autonomic nervous system involves both sympathetic and parasympathetic nervous systems and has a periodical variation but not a single adjustable system. Therefore, the entire autonomic nervous system (ANS) shows a certain activity value; it could not be adopted as a standard to evaluate the performance of comfort. However, it could still confirm whether or not the sympathetic and parasympathetic nervous systems exhibit special variations.

Analyses of the activity of sympathetic nerves (ASN)

Figure 6 indicates that the activity of sympathetic nerves (ASN) of a tester in static mode and the sequences of sympathetic nerve activity in static mode were traditional vest > quick-drying vest >

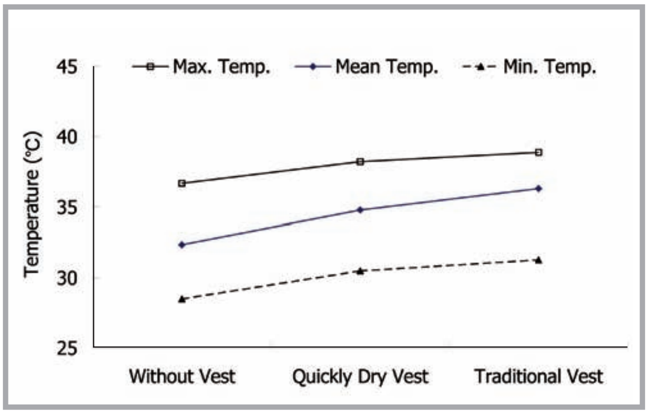

Figure 3. *Chart of tester's skin temperature maximum, mean and minimum for wearing no bulletproof vest; after exercise mode for 10 minutes.*

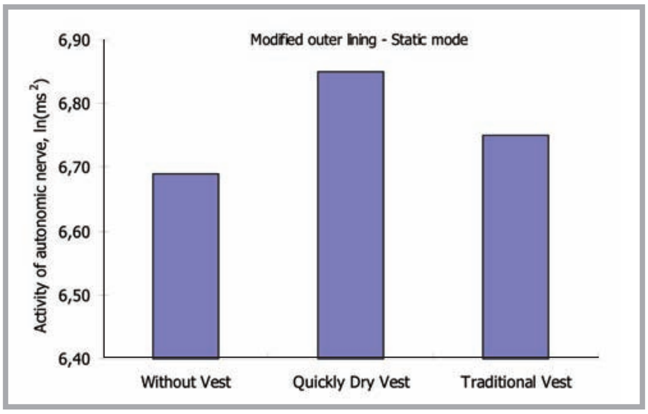

Figure 4. *Chart of activity of autonomic nerves (AAN) for various outer linings in static mode.*

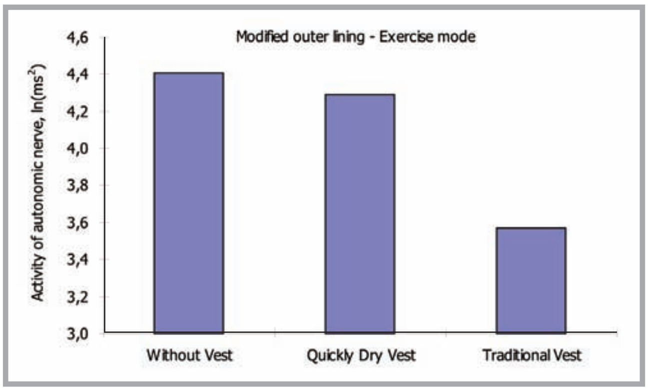

Figure 5. *Chart of activity of autonomic nerves (AAN) for various outer linings in exercise mode.*

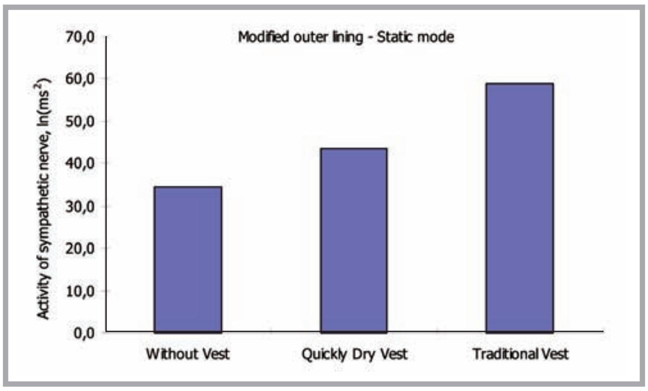

Figure 6. *Chart of activity of sympathetic nerves (ASN) for various outer linings in static mode.*

Table 1. The delicacy, D, for the activity of sympathetic nerves (ASN).

	Non Vest	Traditional Vest	Gap, d	Delicacy, D
Static Mode	34.4	58.9	24.5	71.2%
Exercise Mode	44.1	46.2	2.1	4.8%

Table 2. The delicacy, D, for the activity of parasympathetic nerves (APSN).

	Non Vest	Traditional Vest	Gap, d	Delicacy, D
Static Mode	7.11	6.72	0.39	5.8%
Exercise Mode	3.72	2.62	1.10	42.0%

without vest. ***Figure 7*** shows the activity of sympathetic nerves (ASN) during exercise mode. The sequence of activities of sympathetic nerves (ASN) in exercise mode were traditional vest > quick-drying vest > without vest. These experimental results indicate that the moisture-absorbing and the rapid-drying properties of the fabric used for the outer lining of the bulletproof vest can significantly improve user comfort during physical activity.

Table 1 shows the delicacy, D, for the activity of sympathetic nerves (ASN). The sympathetic nerve activity of the tester was 34.4 in the static situation without a bulletproof vest (the most comfortable condition) and 58.9 in the static situation with a traditional bulletproof vest (the most uncomfortable condition). The difference between the two values, d, was 24.5. The delicacy, D, for the activity of sympathetic nerves (ASN) was defined as the ratio of the difference between both values to the ASN of non-vest ($ASN_{non\text{-}vest}$). That can be described as:

$$D = \frac{d}{ASN_{non\ \mathrm{vest}}} \quad (1)$$

Therefore, the delicacies of ASN were 71.2% in static mode and 4.8% in exercise mode. The delicacy of ASN in static mode substantially exceeded that in exercise mode.

Analyses of the activity of parasympathetic nerves (APSN)

Figure 8 shows the user activity of parasympathetic nerves (APSN) in the static situation. The sequence of activities of parasympathetic nerves (APSN) in static mode were without vest > quick-drying vest > traditional vest.

Figure 9 shows the APSN of the tester in the exercise situation. The trends were similar in the static situation. The sequence of activities of parasympathetic nerves (APSN) in static mode was without vest > quick-drying vest > traditional vest.

Table 2 indicates the delicacy for the activity of parasympathetic nerves (APSN). The APSN in the situation without a bulletproof vest (the most comfortable condition) was 7.11, and that with the traditional bulletproof vest (the most uncomfortable condition) was 6.72. The difference between those two values was 0.39. Equation (1) shows that the delicacies for the activity of parasympathetic nerves (APSN) in static and exercise modes were 5.8% and 42.0%, respectively. The delicacy of APSN in static mode was much greater than that in exercise mode.

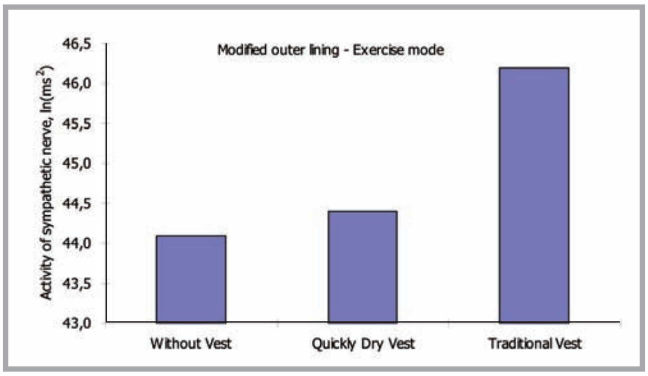

Figure 7. *Chart of activity of sympathetic nerves (ASN) for various outer linings in exercise mode.*

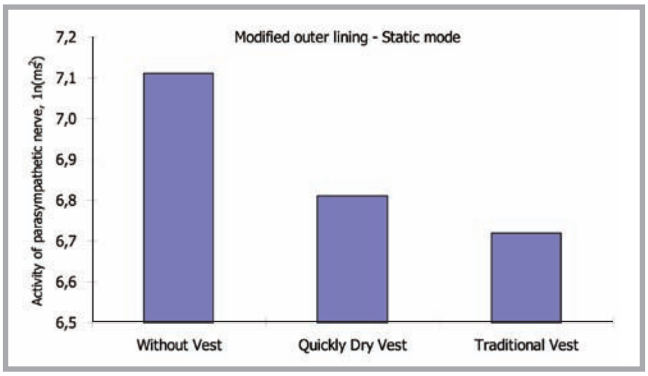

Figure 8. *Chart of activity of parasympathetic nerves (APSN) for various outer linings in static mode.*

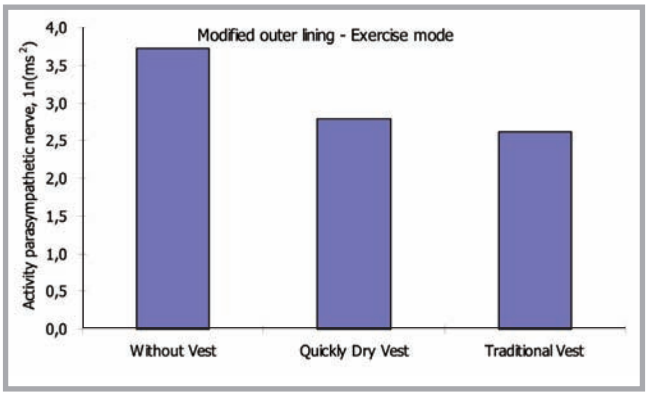

Figure 9. *Chart of activity of parasympathetic nerves (APSN) for various outer linings in exercise mode.*

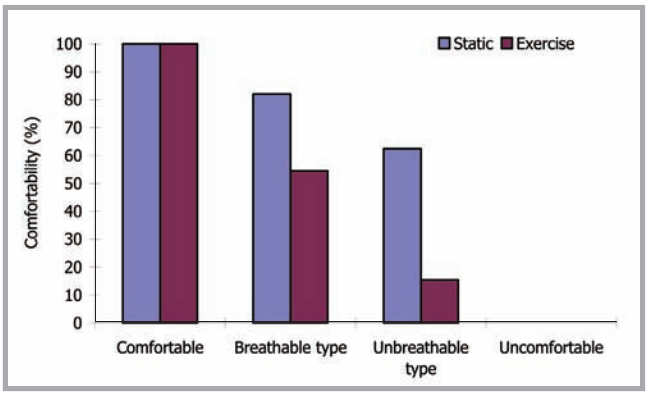

Figure 10. *Comfortability vs. different types of inner lining for bulletproof vest wears in static and exercise modes.*

This study also comprehensively investigated ASN and APSN in the static and exercise situations. The results of the delicacy of nervous activity revealed the following: when using the HRV analyser to carry out the quantitative analysis of the bulletproof vest, it is better to adopt the ASN in a static mode and adopt the APSN in an exercise situation.

Certified cases (increasing the comfortability by improving the breathability of the inner lining)

In order to carry out the practicability for the quantitative analysis of the bulletproof vest, the original nylon fabric of the inner lining was replaced with waterproof and breathable fabric to enhance the comfort of the bulletproof vest further. ***Figures 4-9*** show the results for the static and exercise modes. Based on the analytical results described in the previous section, the static mode preferred the ASN and the exercise situation liked the APSN, respectively. ***Figure 10*** shows the results for comfort measured in the static and exercise modes, where 100% is the most comfortable situation without a vest in static mode and 0% is the most uncomfortable condition with a traditional bulletproof vest.

In order to enhance the comfort of the bulletproof vest, the functional textiles were applied to the traditional bulletproof vest, which produced different effects in static mode: when using the moisture-absorbing, quick-drying outer lining, the comfort of the bulletproof vest rose significantly by 62.4%; when using the waterproof–breathable inner lining, the comfort of the bulletproof vest was 19.6% higher than the previous type, up to 82% in total. ***Figure 10*** shows the exercise results, where comfort of 100% was the most comfortable condition without a vest in exercise mode and comfort of 0% was the most uncomfortable condition with a traditional bulletproof vest. In exercise mode, the effects of functional textiles applied to the traditional bulletproof vest were the following: when using the moisture-absorbing, quick-drying outer lining, the comfort of the bulletproof vest reached 15.5%; when using the waterproof–breathable inner lining, the comfort of the bulletproof vest reached 54.5%, which was 39.9% higher than that of the previous type.

To summarize the above results, the functional textiles applied to the traditional bulletproof vest can significantly enhance comfort in the static mode but has less effect in the exercise mode. The use of the waterproof–breathable inner lining improves comfort in the exercise mode because the waterproof–breathable fabric can accelerate the emission of heat from sweat by exercise so that the comfort of the bulletproof vest is improved.

Conclusion

With the sympathetic nerve and parasympathetic nerve activity, the analysis of heart rate variability precisely illustrates the physiological comfort with the objective data. When using HRV for quantitative analysis of the bulletproof vest, it is better to adopt the ASN in a static mode and take the APSN in an exercise situation. Using a waterproof-breathable inner lining can substantially enhance comfort in the static mode. Although it is also practicable to improve comfort in exercise mode, the improvement in comfort is smaller than that in static mode. The waterproof-breathable fabric can help disperse heat generated during exercise and improve the comfort of the bulletproof vest.

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