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RESEARCH ON COMPREHENSIVE DESIGN MODEL OF INDIVIDUAL EMERGENCY RESCUE PROTECTIVE CLOTHING

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Research on comprehensive design model of individual emergency rescue protective clothing

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ABSTRACT

At present, in the context of world peace and development, natural disasters, public health and accident disasters have occurred frequently. Individual protective clothing plays a vital role in safeguarding the lives of emergency rescue workers. In this paper, a comprehensive design model of individual emergency rescue protective clothing is constructed. In addition, a concept of protective clothing design effectiveness evaluation is proposed according to the functional requirement design mode. This paper comprehensively integrates needs analysis, functional element establishment, and design element collection and selection. Combined with the results of requirements analysis, the functional requirements elements of emergency rescue protective clothing are formed. After analyzing the relevant protection performance indexes of protective textiles, the functional elements of clothing are classified and analyzed, including style, structure, material, color, craftsmanship and accessories. Functional requirements are effectively combined with elements of clothing design. Thereby, an evaluation index system with functional design elements is established. Then a design effectiveness evaluation model is constructed by the method of fuzzy mathematics. Social network analysis is used to calculate the index weights by Ucinet 6.2 software, and the model is analyzed by several protective clothing commonly used in the market. In practical applications, design elements can be selected according to specific protection requirements and application environments to generate initial design scheme. The design model and evaluation system are combined to construct design system for protective clothing. Finally, the application feasibility of the model is verified by examples, which provides reference value. This paper is instructive to systematize and standardize the design of individual protective clothing. The comprehensive design model proposed in this paper can simplify the existing design process of protective clothing and directly evaluate the design product after the digital design. It can be further expanded to study the functional design of other protective textiles.

Keywords: Protective Textiles, Individual Protective Clothing, Design Model, Design Effectiveness, Functional Design Elements, Evaluation Method.

Introduction

In recent years, due to the complex and variable international situation, public accident disasters have occurred frequently over the world, which pose a great challenge to emergency relief. According to the report of "the Swissre institute", the average global loss from natural and man-made disasters was as high as $212 billion between 2010 and 2019 (Zhang, et al., 2022). The casualties of rescuers are one of the practical problems to be solved. Rescuers would face dangerous situations in work environments. Personal protective equipment (PPE) is one of the key points to ensure the safety of rescuers and improve the efficiency of on-site rescue (Zhai, et al. 2016; Shaid, et al., 2018; Kothari, and Chakraborty, 2016). It has several protective functions that ranges from thermal, chemical, mechanical, biological, radiation, to visibility (Fatarella, et al., 2014). Since clothing constitutes the safety barrier between the wearer and the source of potential injury, its characteristics will determine the degree of injury suffered in case of an accident or an emergency operation (Horrocks, and Anand, 2004). The individual protective clothing should have functional characteristics such as waterproof, anti-static, etc. (Zhang, and Bai, 2012). Structural design can significantly impact physical movement. The design and development of individual emergency rescue protective clothing is from safety engineering, technical aesthetics, human physiology, individual psychology, and system environment. As there may be various unknown potential risks at the rescue site. Single-function protective clothing does not protect against all kinds of damage. The multifunction design and performance evaluation are needed. This study summarizes and analyses the design indicators based on application requirements survey. Combine functional requirements with design elements. The emergency rescue protective clothing design system and evaluation model are proposed. The two parts are interlinked, and the comprehensive design model of individual emergency rescue protective clothing is constructed.

Literature review

At present, most research focus on the special functions, especially the new fabrics. There is much research on the properties of materials such as wet resistance, thermal resistance and comfort (Bell, et al., 2000; António, et al., 2009; Antonin, and Zdenek, 2006). Only a few studies focus on the structural design of protective clothing for emergency personnel. There is fewer comprehensive research.

Wang J. et al., (2019) develop a comprehensive analysis software to simulate damage to human skin, trunk, and respiratory system in typical disaster environments. The software system enables rapid assessment of risk level to various disaster environments. It can evaluate the protective performance of PPE. Wang S. T. et al. (2021). develop a versatile fire protective clothing for the elderly through demand analysis and design feature screening that provides greater body coverage and better thermal protection, as well as flexibility for the elderly leg activity. Li J. H. et al. (2021). propose methods for the sustainable and optimized design of PPE. Such as multi-function shield, detachable design details, multi-bag hidden design, internal stitching elastic belt structure and tightening design to strengthen clothing openings. Teyeme Y. et al. (2021). review four ways to measure the comfort of wearing protective clothing: a combination of subjective assessment, objective observation, subjective and objective techniques, and computer model of human-textile interactions. Study shows that subjective analysis of comfort is less reliable than objective analysis. Jeon E. et al. (2015) design methods

for obtaining protective clothing suitable for the human body.

By disassembling non-woven disposable protective clothing into editable software mode files. Liu H. B. et al. (2021). discuss medical clothing design for epidemic prevention. According to the functional requirements, a simulated infiltration test of pathogenic bacteria is designed to test the protective function of anti-epidemic clothing. There are now a variety of protective clothing on the market, as shown in **Figure 1**. Various types of rescue protective clothing in the professional performance of repeated crossover. In this study, the design system of emergency rescue protective clothing is built from the aspects of demand analysis, function element establishment and design element collection and screening.

Figure 1. Overview of Various Types of Protective Clothing

Methodology

Elements Establishment and Collection Functional Elements. The functional elements are related to the utility of the clothing. The clothing function is specific according to the performance parameters. The clothing function is systematic. The functional elements of protective clothing include protective function, use function and wearing comfort function.

Protective function. For protective clothing, the system is designed to protect the wearer from environmental hazards and to perform tasks smoothly.

Use function. The use function ensure that rescuers can function during the process and improve the work efficiency. The following requirements should be realized: 1) rescuers be able to move freely during the operation requires; 2) common tools and equipment are carried easily to move; 3) consumption performance and use limits are reduced, including wear resistance, dirt resistance, after multiple washing protective properties cannot be reduced; 4) rescuers can easily remove for maximum rescue time when performing an emergency mission.

Wearing comfort function. The comfort of protective clothing is often evaluated with tactile performance, such as thermal and humid comfort, and moisture-absorbing. Protective clothing is a relatively closed system, the overall comfort is influenced by fabric characteristics and clothing structure. Wearing comfort can be divided into four main aspects: 1) heat and humidity comfort (Richmond, et al., 2013; Fontana, et al., 2016; Tian, and Li, 2020), affecting human body temperature regulation, related to heat and moisture; 2) contact comfort (Stoffberg, et al., 2015), related to the fabric contact skin mechanical sensation, such as smoothness and softness; 3) pressure comfort (Brubacher, et al., 2021), which involves clothing fit, the range of motion of various body joints, and freedom of movement; 4) psychological comfort (He, et al., 2016), influenced by individual senses, work environment and other factors.

Design Elements. A successful design is critical and affects the safety of life under extreme conditions. By collecting and finishing the design elements of emergency rescue protective clothing, it is also necessary to further screen the design principles and design characteristics. According to the different application requirements, combined with the limitations of the standard specifications, to obtain the feasibility scheme. The silhouette of clothing is an external shape. From the view of design, single pieces design like the coat and trousers are easy to wear and less restrictive to body movements. Clothing silhouette should be considered depending on rescue apply requirements. The silhouette classification of protective clothing is shown in **Figure 2**.

Design Hierarchical Analysis

Hierarchical clustering algorithms are the common technique that reveals the multilevel structure in the network analysis (Liu, and Zhao, 2019); Faran, and Kupferman, 2019). Hierarchical analysis for network structure can point out which communities can constitute a larger group or give reasonable smaller groups within a community (Luo, et al., 2019).

In this study, the hierarchical analysis is applied to the refinement of design principles and the selection of design methods. According to its importance, the design principles are divided into three different levels, including the necessary principles, general principles and recommended principles, as shown in **Table 1.**

Level I is the safety protection function that must be met by different rescue environmental protective clothing. Level II is the common basic requirements of rescue protective clothing to ensure that rescuers are comfortable to wear, meet ergonomic activity needs, and prevent physical and mechanical damage. Level III includes recommended principles based on improving the use of protective clothing.

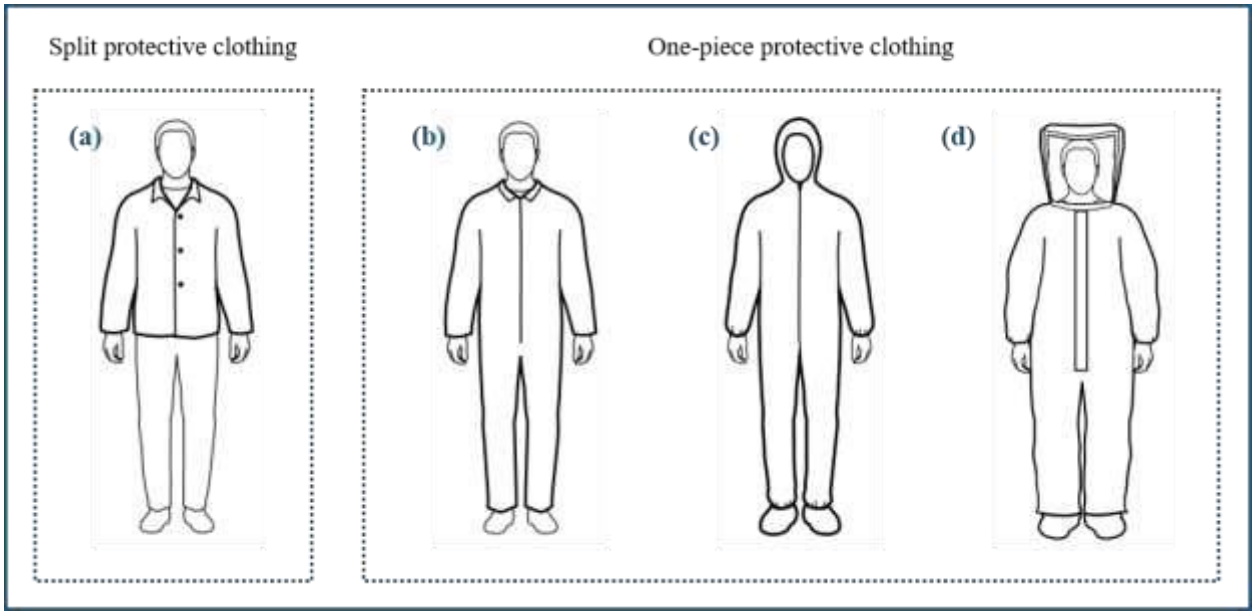

Figure 2. Protective Clothing Silhouette Classification

Table 1. Three levels of design principles for emergency rescue protective clothing.

Principles	Functional elements	Purposes	Delivery methods
Level I - necessity principles	Overall thermal protection Flame retardant property Waterproof insulation Anti-chemical permeability Barrier property Radiation shielding property. Anti-static property	Safety protection	Fabric Structure Technology Attachment
Level II - general principles	Thermal and humid comfort Contact comfort Pressure comfort	Wear comfortable	Fabric Structure
	Easy to wear. Flexible operation Fit	Activity efficiency	Fabric Structure Attachment
	Abrasion resistance Tear resistance Fatigue resistance Anti-hook hanging	Mechanical strength	Fabric Structure Attachment
Level III - recommendation principles	Durability High visibility Appearance Compatibility	Use function	Fabric Technology Attachment

Design Effectiveness Evaluation Model

Indicators System Establishment. Combined with functional requirements, this study summarizes the influence factors of the design effectiveness of protective clothing and improves the evaluation index system of design effectiveness. According to the functional requirements, establish a network of performance evaluation indicators of protective clothing design, the evaluation indicators are graded and numbered.

Indicators Weight Determination.

The production process of all links, aspects, factors of protective clothing are interrelated. By constructing a network of indicators, it can provide a clearer and deeper understanding of the performance factors of protective clothing to guide production. Therefore, this study uses Netdraw, a visualization module in Ucinet 6.2 software to map the correlation between evaluation indicators, as shown in **Figure 3**. Based on the established metric network matrix, using the social network analysis software Ucinet 6.2 the central operation of the metric and the normalized processing of the result to 0 ~ 1 interval, convenient index weight calculation and comparison. The final results are normalized and weighted against the evaluation system indicators, as shown in **Table 2**. Finally, the weight of each evaluation indicator in the overall evaluation network is obtained. From the indicator weight results, the comprehensive properties of fabrics remain the most important part of the design elements of protective clothing. Colours is less relevant and influential to other parameters. This also

coincides with the hierarchy of protective clothing design principles established in this study. The indicators data are more rational and well-referenced, which can be used as a system of evaluation indicators metric weights in the network.

Fuzzy Comprehensive Evaluation.

Fuzzy comprehensive evaluation method is a method of objective evaluation and judgment of many factors, such as people, objects, things, procedures, etc. It is used to express the uncertainty of things. The evaluation content and standard of the effectiveness of protective clothing design are fuzzy. Therefore, the fuzzy comprehensive evaluation method is used. The evaluation factors set is all 3-level indicators. The comment set is an element set of the answers to the survey content. After testing and discussion, the review set is divided into 4-level $V =$ $\{v_1, v_2, v_3, v_4\}$ $=$ $\{Poor, Medium, Good, Excellent\}$ The corresponding rating value is [60, 70, 80, 90]. A comprehensive analysis of the evaluation result vector is carried out according to the weighted average principle to determine the level of the system. Finally, the evaluation results are transformed by percentage. Then, get comprehensive evaluation value $E = B' \cdot H^T$. Where the score set vector corresponding to "Poor, Medium, Good, Excellent" is H = [60, 70, 80, 90].

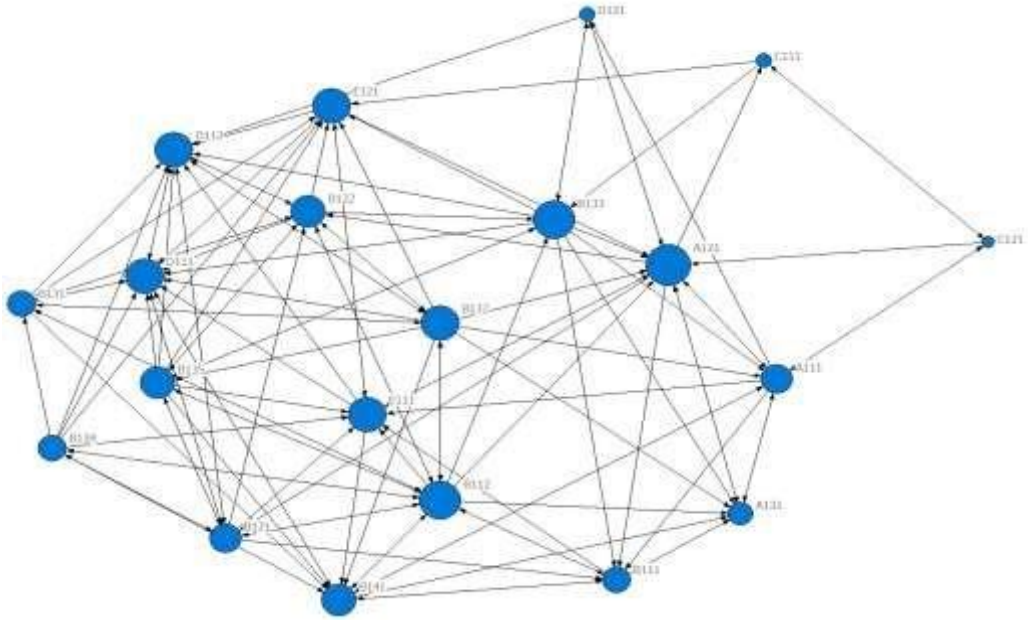

Figure 3. Network Diagram of Evaluation Indicator System

Table 2. Performance evaluation indicators weight for protective clothing design.

Target level	Level I indicators	Level II indicators	Level III indicators
Protective clothing design effectiveness U (1)	Materials A1 (0.162)	Material type A11 (0.051)	Fabric combinations A111 (0.051)
		Material properties A12 (0.070)	Comprehensive performance A121 (0.070)
		Fabric touch A13 (0.041)	Fabric touch A131 (0.041)
	Structures B1 (0.522)	Clothing air gap B11 (0.106)	Specification design B111 (0.045)
			Relaxation volume B112 (0.061)
		Clothing opening B12 (0.101)	Natural openings B121 (0.049)
			Unnatural openings B122 (0.052)
		Site structure design B13 (0.261)	Pleated B131 (0.044)
			Split B132 (0.057)
			Overlap B133 (0.064)
			Tightness B134 (0.044)
			Zipper B135 (0.051)
		Overall profile design B14 (0.053)	Fitness B141 (0.053)
	Colours C1 (0.057)	Cautionary C11 (0.031)	Reflective material C111 (0.031)
		Recognizability C12 (0.026)	Contrast C121 (0.026)
	Technologies D1 (0.143)	Closure type D11 (0.112)	Convenience D111 (0.055)
			Seal D112 (0.057)
		Seam type D12 (0.031)	Seam strength D121 (0.031)
	Attachments E1 (0.115)	Suitability E11 (0.057)	Suitability E111 (0.057)
		Versatility E12 (0.058)	Versatility E121 (0.058)

Results and discussion

Comprehensive Design Model

In the design and development of emergency rescue protective clothing, the first should analyse the application scenario of rescue protective clothing. Establishing protection objectives, summarizing hazard factors and rescue characteristics. Next, the application needs study and analysis. To establish the functional requirements of the target object and the realization of the elements of protective clothing design. Comprehensive analysis results in optimal design and performance measurement and feedback re-design. This study summarizes the process and thought of the above constructs the framework of the comprehensive design system of emergency rescue protective clothing, as shown in **Figure 4**.

Application Scenario Analysis. Different kinds of protective clothing have their applicable environment. After establishing protection objectives, the natural working environment and task-related hazards should first be identified. and whether it causes harm to the human body. This allows for targeted setting of basic protection performance requirements.

Application Requirements Research. In the research stage of protective clothing design, target population needs research and analysis. Combined with field visits, questionnaires, audio recording, network communication methods and other ways to understand the needs of all aspects. After confirming the protection goal, observe the scene of the rescue training, interview the target rescuers in depth. And personally try on the rescue protective clothing for a more intuitive understanding. After understanding the broad scope of requirements, the questionnaire is used to conduct targeted surveys, obtain information on common movements, produce

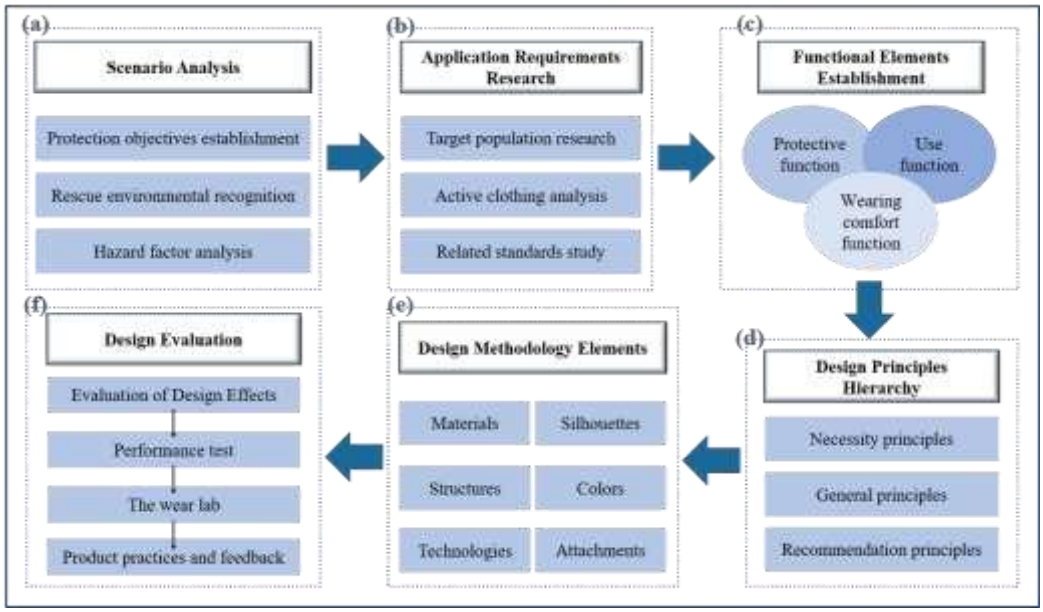

Figure 4. Emergency Rescue Protective Clothing Design System Framework

discomfort sites and the most vulnerable sites, as well as the necessary design for retention of protective clothing.

Functional Elements Establishment

Through the research to obtain the application requirements of the protection goal, need to translate the problem and requirements into the design step of the functional elements, that is, protective clothing to meet the needs of the wearer's functional properties, mainly protective function, use function and wear comfort function three categories.

Design Elements Collection. The realization of functional elements depends on the integration of the design method. The designers should choose the design methods to meet the requirements. Common methods are fabric selection, structure design, colour design and the use of appropriate protective accessories.

Prototype Design Scheme. Through the emergency rescue protection clothing design methods and factors of understanding. Based on the requirements of the standard specification, combined with the findings of the application requirements, formulating the scheme of protective clothing for target population. Then, the design drawings are obtained, and sample clothing are made.

Design Evaluation and Testing

Theoretically, the design of protective clothing needs to undergo many experimental tests and continuous improvement, the performance of the test and evaluation is a key step before use. Based on the functional design research concept, the evaluation stage consists of four steps: design performance evaluation, performance testing, wearing experiment and product practice. The feedback results from the practice will further cycle the design system until the best solution is put into the market.

Virtual Practice of Design System

Since the target population is emergency rescuers, this design focuses on the emphasis on versatility. The individual emergency rescue protective clothing should be able to respond to sudden-onset disaster risks while adapting to everyday work scenarios. Therefore, this study focuses on application of functional elements. The comprehensive design of rescue protective clothing, from

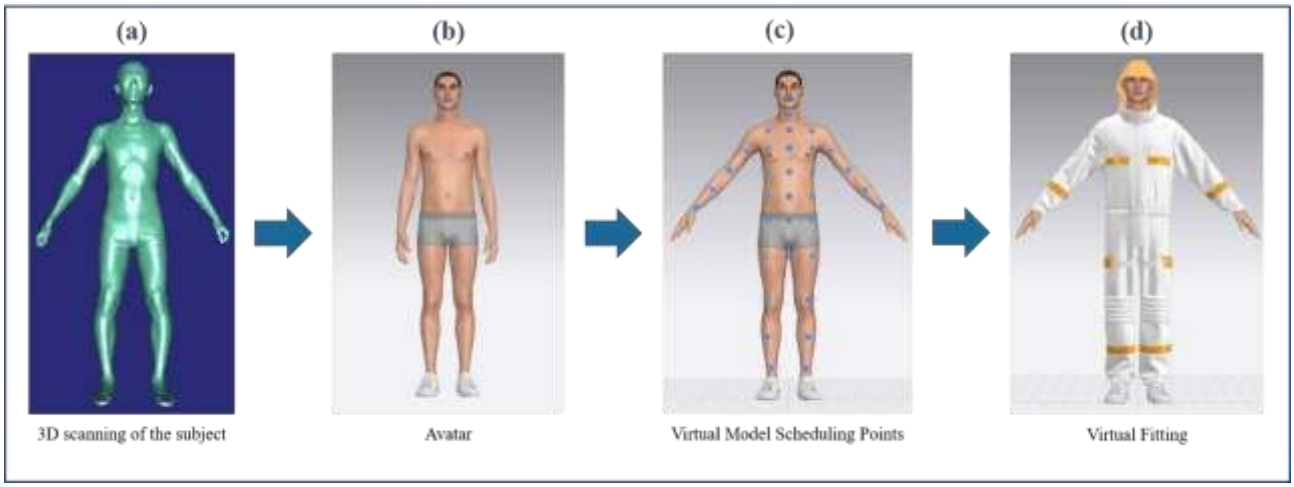

Figure 5. Virtual Clothing Making Process

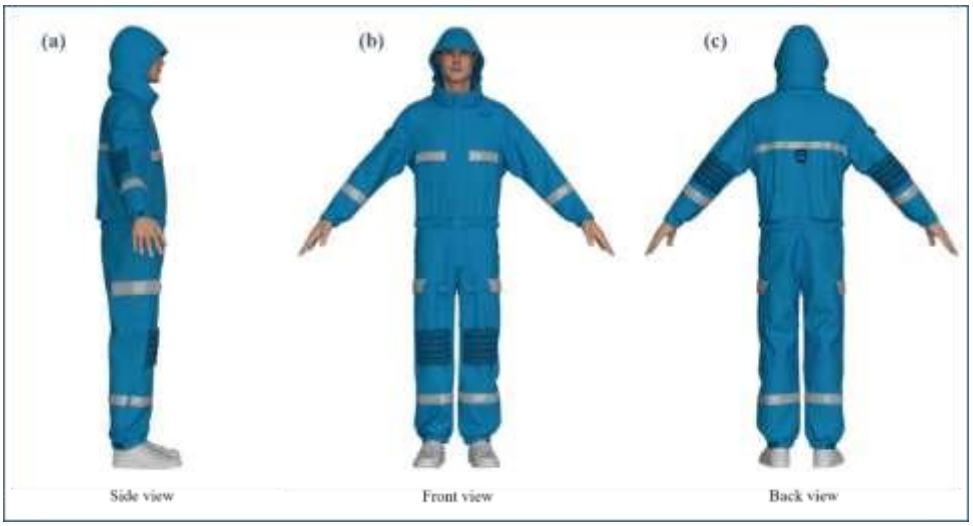

Figure 6. Virtual Rendering of Emergency Rescue Protective Clothing

structure design and auxiliary life-saving functional design.

According to the functional design method, a virtual design of emergency rescue protective clothing is practiced. **Figure 5** shows the design process of an individual emergency rescue protective clothing. The method of the design process is completed by individualized dimensional parameter change and 3D cutting. The human data is obtained by AnthroscanM4 3D body scanner to establish virtual model in CLO3D 5.0 version software to adjust the joint and body size data of virtual model so that it is consistent with the scanned human data. Adjust the fabric physical parameters at the fabric properties interface to get the right appearance. The results are 3D fitting diagrams with realtime rendering, as shown in **Figure 6**.

Design Effectiveness Evaluation of Virtual Protective Clothing.

This study uses CLO3D 5.0 version software for virtual fitting and design effectiveness evaluation. This study verifies the reasonableness and feasibility of structural design through virtual fitting experiment. Virtual design effectiveness evaluation is more convenient to operate than the human wearing test, the experimental results are intuitive and clear. The design effectiveness evaluation begins with the purpose of functional design and analyses the degree of

the design effectiveness to obtain the best solution in the actual design and development process.

Structure Design. Based on the design requirements and application of multiobjective, this study designs a general-purpose individual emergency rescue protective clothing.

Convenient wearing design. For convenient use, combined design of zipper at the waist and hips, as shown in **Figure 7 (a)**. The front waist is elasticated design, connected to the rear waist hip ring zipper. The opening zipper of the front extends to the crotch to improve the overall wear convenience. The hat, cuffs and bottom leg openings are provided with elastic buckle design, easy to adjust and wear, ensure the protective function in harsh environment. *Pleat thickening design*. To provide mobility adaptations, dark pleats and thickened padding are used at the knees and elbows of emergency rescue protective clothing. Increasing the range of movement of the elbow and knee joints while preventing wear.

Open ventilation design. Combined with the warming characteristics of various parts of the body and the level of sweating during vigorous exercise. Remove natural opening areas such as necklines, cuffs, and bottom leg openings in emergency rescue protective clothing. Add openings at armpits. At the back, there are lateral segmentation to ventilate the openings, and control the openings by zippers.

Function Effectiveness. The principles of functional design are analysed. The design would improving the functional design elements, through clothing design to achieve functionality.

Storage function design. A total of seven pockets ensures efficient use of storage features. Pockets for arms, chest, waist and both sides of legs are convenient for rescuers to carry out matching tools, and bag cover with zipper seal.

Self-rescue fire protection design. The hat zipper connection of the rescue protective clothing is freely detachable. The bottom of the hat hidden the hooded fire protective cape that increasing multi-scenario applicability, as shown in **Figure 7 (b)**. Flame retardant zippers can be quickly opened in case of sudden fire risk. Around the whole body to form a sealed protection range, and with hooded can be tightened cap port. Reduce exposure area and increase chances of survival. *Safety lifebelt design*. Based on the structural stability of the anti-fall component, the safety lifebelt is embedded between the inside and outside layers, as shown in **Figure 7 (c)**. Assist in lifesaving and improve the functionality. The safety lifebelt is designed with multiple external adjusting buckles to relieve the pressure constraint of local forces, while increasing stability.

Pressure Comfort. The overall pressure distribution can be tested and adjusted with the pressure test module in CLO3D. The degree of pressure is reflected in the mesh diagram of the clothing surface, as well as numerical and colour. According to the size of the pressure value, the fit degree of the garment and the loose amount of the parts can be identified. **Figure 8** shows the pressure distribution map when the model arm is raised 45 °. The shoulder and arm seam can be seen, the overall body of the rescue suit is basically unencumbered, pressure comfort is good, can meet the daily activities required for loose.

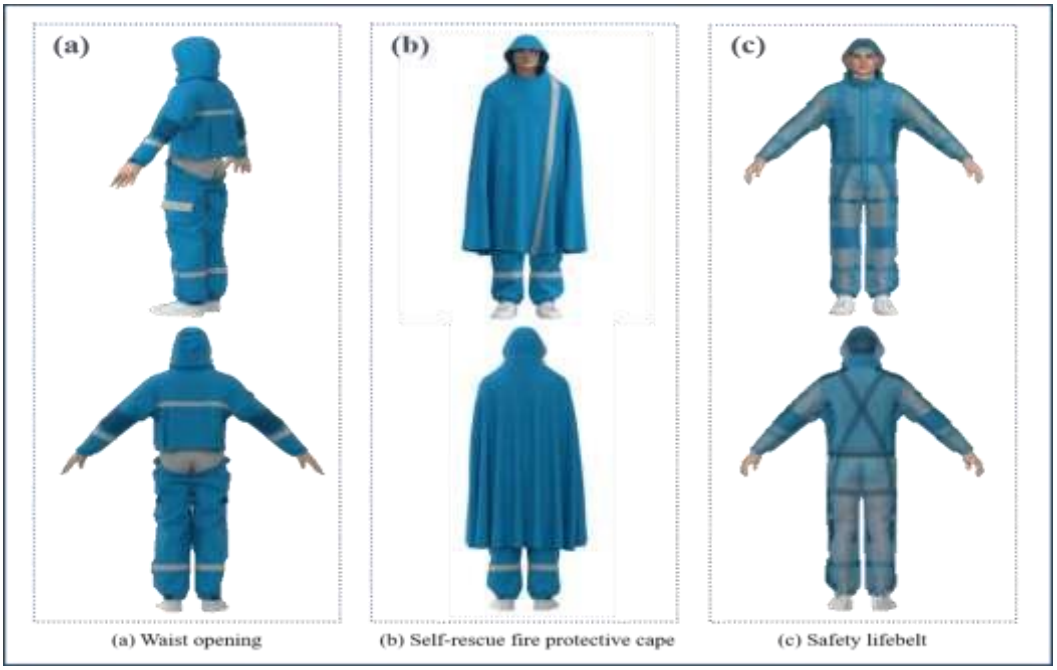

Figure 7. Safety Protection Function of Emergency Rescue Protective Clothing

Figure 8. Pressure Distribution of Emergency Rescue Protective Clothing

Conclusion

This study presents a functional modular design model for designing and evaluating individual emergency protective clothing. The functional design elements are defined as protection, use and wearing comfort. The relevant design indicators are described by hierarchical analysis. Three levels of the design principle of emergency rescue protective clothing are established, namely the necessary principles, general principles, and recommended principles. And social network analysis centre is used to empower the indicators. Fuzzy mathematical method is used to construct comprehensive evaluation model. The function design mode of emergency rescue protective clothing was constructed, and the effectiveness evaluation system of emergency rescue protective clothing was extended. Based on the design system, the design needs and application range of multiobjective, universal, design a universal emergency rescue protective clothing.

Combined with 3D virtual fitting and its linkage technology, the design products are presented and evaluated. The feasibility of integrated design system is verified. The comprehensive design system proposed in this study can optimize the design method and process of emergency rescue protective clothing. In addition, the method can evaluate the degree of functional demand satisfaction. This study provides a value method for the design and development of functional emergency rescue protective clothing and performance evaluation.

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