Development of a thermal comfort management system in heat-protective clothing for people with disabilities

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Abstract. The article deals with the development of a thermal comfort control system in thermal protective clothing for people with limited motor capabilities. In particular, the stages of forming the thermal comfort control system are described, and testing of the proposed system in real environmental conditions is carried out. The aim of the work is to develop and scientifically substantiate a thermal comfort control system used in thermal protective clothing for people with limited motor capabilities. The relevance of the paper is conditioned by the increased need for special heat-protective products with the function of control and monitoring of thermal comfort for people with limited motor abilities, who use a wheelchair as a means of transportation in everyday life. The work is based on the use of a systematic approach to the design of heat-protective adaptive clothing for people with limited motor capabilities. To solve a set of tasks the methods of mathematical modeling and experimental research were applied. The methods of system analysis and the basics of digital circuitry were used in theoretical research. The algorithm of the thermal comfort control system operation was substantiated and software for a smart phone was developed to control and monitor the temperature of underclothing space in a heat protective product for people with limited motor capabilities and findings are presented in the research work.

1. Introduction

The problem of universal integration of people with disabilities into social life is a strategic task of the Government of the Russian Federation. At the same time, people with limited motor capabilities (PLMC) are not provided with comfortable clothing that meets their physiological needs [1].

So, the important factors are to be taken into account when designing heat-protective adaptive products for PLMC are thermoregulation disorders, the absence of an objective reaction of the hypo dynamic system of the lower extremities of PLMC to external stimuli (negative ambient temperatures). These factors increase the risk of freezing and uncontrolled frostbite of the lower extremities.

At present, the theoretical and regulatory framework for designing adaptive clothing for PLMC is poorly developed, including the temperature changes on the skin surface of PLMC as compared to the group of healthy people, there is no general understanding of thermoregulation processes and circulatory disorder mechanism, there are no criteria for determining a comfortable physiological state of a person with limited motor capabilities (LMC) in connection with a huge number of causal relationships leading to a person’s disability [2].

In the Russian Federation, the leading companies for the production of functional thermal protective clothing for PLMC are Bryansk Prosthetic and Orthopedic Enterprise [3], LLC Center of Designing
Special Purpose Shoes ORTOMODA (LLC CDSPS ORTOMODA, Moscow) [4], LLC «Cryptomed» [5] (Moscow) and the Federal State Budgetary Institution «St. Petersburg Scientific and Practical Center for Medical and Social Expertise, Prosthetics and Rehabilitation of Disabled People named after G.A. Albrecht of the Ministry of Labor and Social Protection of the Russian Federation» (St. Petersburg) [6]. The leaders in the production and sale of special (adaptive) clothing for PLMC among foreign manufacturers are the brands Buck & Buck [7], ABL Denim [8], Adaption by Adrian [9], Easy Access Clothing [10] (USA), Izadaptive [11], Silvert’s [12] (Canada), Able2Wear [13] (Great Britain). At the same time, as a detailed consideration of the issue shows that the problem of designing special heat-protective clothing for PLMC, with a thermal control device, remains insufficiently studied [14].

The solution of the problem of maintaining a comfortable thermal state of PLMC in negative ambient temperatures is the use of smart clothing elements in the design of the product, in particular, a local heat system (LHS) and a thermal comfort control system (TCCS) based on the ESP-WROOM-32 microcontroller.

One of the most important tasks in the design of a heat-protective product with LHS is the choice of adequate heat temperature for various climatic conditions. Taking into account the complexity of an objective assessment of PLMC based on thermal sensations and preferences, the authors experimentally determined the permissible temperature conditions for PLMC in heat-protective clothing with a local heating system at negative ambient temperatures.

For the first time, the average values of the skin surface temperature in the areas of the hypo dynamic system of the lower extremities of the PLMC in the comfort zone, and its variability limits were determined as a theoretical justification for the technical task of designing heat-protective products for the PLMC. It was found that the average surface temperature of the skin of the hypo dynamic system of the lower extremities of healthy people exceeds the average value of the skin surface temperature of PLMC by 0.8°C with a variation in individual areas from 0.5 to 4.4°C. The areas of the greatest and the least deviation of the mean values of the skin temperature of the lower extremities of the group of healthy people and PLMC were determined.

The results of the previously obtained experimental data formed the basis for the development of an algorithm of the TCCS operation with the function of controlling and monitoring by means of the smart phone software. The authors consider that it possible to present the results of the experimental and theoretical research in the framework of achieving the goal – the development of a thermal comfort management system in a heat-protective product like a bag for feet for PLMC.

2. The development of a thermal comfort management system in a thermal protective product for PLMC

One of the important factors in equipping a heat-protective product with heating elements for PLMC is the choice of a temperature regime range under various situational environmental conditions, i.e. heat in the product should be controlled automatically in response to changes in preset conditions. In other words, the heat system must be safe during operation and take into account main person’s physiological characteristics with physical inactivity of the lower extremities, first of all, such as impaired skin sensitivity – reactions to external stimuli. Since a person with LMC, when exposed to heat on body parts, without an adequate response to a stimulus (for example, with a violation of body functions as paraplegia) can get a thermal burn.

This increases the need to control temperature changes due to additional heating sources. To solve this problem, an operation algorithm of the thermal comfort management system has been developed, taking into account the use of a local heat system. The proposed algorithm is shown in figure 1.
Figure 1. Algorithm of the thermal comfort control system, where $t_1$ – is the temperature of the heat element; $t_2$ – is comfortable temperature.

The presented algorithm of the TCCS operation has a temperature hysteresis equal to 2°C, embedded into the logic of the thermostat. Suppose that the user has set the temperature of the heating elements to 36°C, while the temperature hysteresis is 2°C. If the temperature drops to 34°C, the thermostat turns on and when the temperature inside of the product reaches 36°C, the thermostat goes off. For the safe operation of the product with heat elements the use of an external mobile battery («Power bank») is proposed.

Figure 2 shows the TCCS diagram. The principle of operation of the TCCS is that the product is equipped with a control microcontroller (ESP-WROOM-32) (1), with a power management system with a built-in Bluetooth bridge (2), a system that reads the temperature of the heating elements, equipped with a thermal sensor (3), which in its turn measures the temperature inside of the under-clothing space, as well as a system of switching on and off the heat elements (4).

Figure 2. Diagram of the thermal comfort control system.

To control and monitor the desired temperature inside of the product, smart phone software has been developed. The algorithm of TCCS operation is recorded on the control microcontroller. Using Bluetooth on the smart phone, the user connects to the heat-protective product, and sets the desired temperature inside of the product by means of the application. Figure 3 shows the interface of a prototype application for a smart phone with the working title «THERMOBAG»

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3. Approbation of a heat-protective product for PLMC with a thermal comfort control system

The approbation of a prototype of a heat-protective product with TCCS was carried out according to a method similar to that given in [15]. At first, a heat-protective product was selected, consisting of the main material — membrane fabric, a gasket insulation material-Tinsulate® and a lining material-fleece Mesh neoprene was used to make pockets for the local system and TCCS elements. The elements of the additional insulation layer are made of foiled material penofol.

The tests were carried out in laboratory conditions with artificially set parameters, in the initial stage of the test the subjects were sitting (when simulating the air temperature of minus 15°C as the extreme temperature of the declared range), relative air humidity (60-65%) and air mobility no more than 0.2-0.4 m/s), the participants were six men aged 45-60 who can move by means of wheelchairs, being the second group of limitation of motor activities according to the PLMC classification (with spinal lesions brain at the level of the lumbar spine) (with a confidence level of 0.95 and an acceptable error of 5%). The total disability experience of the subjects was more than 10 years. All the subjects were dressed in household clothing: underwear, thermal underwear, an over shirt, warm trousers, a sweater, warm socks, an insulated jacket, a hat and gloves. All studies were carried out under the supervision and direct participation of workers of medical institutions, as evidenced by the act of conducting joint research on the basis of state budgetary institution of social services of the population of Rostov region Shakhty boarding house for the elderly and disabled (Shakhty, Rostov region). Figure 4 shows photographs before the experiment (10 minutes of rest before the experiment).
The results of experimental wearing for five days (taking into account the duration of the walk no more than 1 hour) showed a high degree of statodynamic conformity of the product and thermal comfort. Additionally, an improvement in the emotional state of the subjects during and after the walk was recorded. At the same time, the subjects themselves noted that the complex heat-protective product is convenient for self-putting on and taking off. Increasing the degree of self-service, comfort and safety of the product for all subjects became fundamental in determining the «feet bag» as a priority and desirable for everyday wear in winter.

4. Conclusion
The use of modern technologies and various technical devices leads to an increase in the quality of life of people with disabilities. Thus, in the course of the research work, the following results were obtained:

- for the first time, the use of the thermal comfort management system of the hypo dynamic system of the lower extremities in the operation of heat-protective products for PLMC in conditions of negative ambient temperatures is proposed, which allows creating and controlling a safe and comfortable temperature of the under-clothing space;
- the software for the smart phone is developed to control and monitor temperature of the under-clothing space;
- the functional and constructive device of the thermal protection product for PLMC has been improved, taking into account the use of a local heat system and STCS. A method for designing the feet bag in the conditions of functioning of computer-aided design system (CADS) «Grace» is proposed.

As part of the further development of research on the problem considered in this article, it is planned to improve the methodological apparatus for analyzing thermo physical processes and the choice of structural elements of heat-protective clothing.

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