Investigations for the development of smart trousers for paraplegic wheelchair users. Part 2 – Development of a test prototype of smart heating trousers

DOI: 10.35530/IT.075.01.202325

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ABSTRACT – REZUMAT

Investigations for the development of smart trousers for paraplegic wheelchair users. Part 2 – Development of a test prototype of smart heating trousers

The main objective of this research was to develop smart trousers for paraplegic wheelchair users to improve the thermal comfort of their lower extremities when exposed to cold environments. In this part of the research, a test prototype of smart heating trousers was developed and tested on the thermal manikin. The development of the test prototype of the smart heating trousers is based on the design recommendations explored in the first part of this paper. The design recommendations relate both to the development of a trousers pattern design for the sitting posture of wheelchair users and the possibility of integrating electrical components into the trouser design, as well as the development of a smart heating system that provides safety for the wearer of the trousers. The results of this part of the research show that the developed smart heating trousers can improve the thermal insulation of the legs and the thermal comfort of the wearer. This is ensured by a carefully planned and safe algorithm that automatically regulates the temperature of the microclimate inside the trousers.

Keywords: *paraplegics, cold protection, thermal comfort, smart heating trousers, thermal insulation*

Investigații pentru dezvoltarea pantalonilor inteligenți pentru utilizatorii cu paraplegie în scaune cu rotile. Partea 2 – Dezvoltarea unui prototip de testare ai pantalonilor inteligenţi cu încălzire

Obiectivul principal al acestui studiu a fost de a dezvolta pantaloni inteligenți pentru utilizatorii cu paraplegie în scaune cu rotile, pentru a îmbunătăți confortul termic al extremităților inferioare atunci când sunt expuse la medii reci. În această parte a studiului, a fost dezvoltat și testat un prototip de testare ai pantalonilor inteligenţi cu încălzire pe manechinul termic. Dezvoltarea prototipului de testare al pantalonilor inteligenţi cu încălzire se bazează pe recomandările de proiectare explorate în prima parte a acestui studiu. Recomandările de proiectare se referă atât la dezvoltarea unui model de pantaloni pentru postura de șezut a utilizatorilor în scaune cu rotile, la posibilitatea de a integra componente electrice în designul pantalonilor, cât și la dezvoltarea unui sistem inteligent de încălzire care oferă siguranță purtătorului de pantaloni. Rezultatele acestei părți a studiului arată că pantalonii inteligenţi cu încălzire dezvoltați pot îmbunătăți izolarea termică a picioarelor și confortul termic al purtătorului. Acest lucru este asigurat de un algoritm atent planificat și sigur care reglează automat temperatura microclimatului din interiorul pantalonilor.

Cuvinte-cheie*: persoane cu paraplegie, protecţie la frig, confort termic, pantaloni inteligenţi cu încălzire, izolaţie termică*

INTRODUCTION

Health is wealth, and we can support it with appropriate garments, especially when there is heat or cold stress on a person. With smart garments, we can protect people from cold stress by putting them in a thermally neutral or comfortable state. Paraplegics are particularly exposed to cold stress due to poor blood circulation in the lower limbs and the associated regulation of body temperature and hypothermia of the lower limbs. Therefore, we need to provide them with functional textile materials and clothing systems that can prevent cold stress.

The realisation that multi-layer clothing systems compress the inner layer of air, reducing its thickness and significantly decreasing the insulation of the garment, is likely to encourage the development of functional textile materials for cold protection that are thinner and provide better thermal insulation than the multi-layer clothing systems we used to wear. Multi-layered clothing systems are also usually stiffer and restrict the user's freedom of movement. Today, people are striving for ever greater comfort and clothing is becoming thinner and thinner while still providing the same level of warmth as thicker clothing [1] or multi-layer clothing systems. Smart heating clothing can meet these requirements very well and its concept was developed a long time ago [2].

Based on the advantages and disadvantages of personal heating garments described in the article by Wang et al. [3], it was found that electric heating garments have a promising feature. At the same time, they pointed out that the battery power does not meet the demands placed on electric heating clothing for long stays in cold environments. Today, functional textile materials and miniaturised electronic components enable the realisation of smart garments that improve or extend the functionality of ordinary garments. Together with mobile phones, they include applications that have an easy-to-use interface and use Bluetooth as a wireless communication method [4]. To avoid the risk of disease and physical harm and to increase thermal comfort, various personal heating systems have been developed to provide thermal comfort to the body through integrated heating units, e.g. heated garments, heated socks and gloves, heated insoles [5]. In this article, four types of personal heating systems (electrically heated seat, electrically heated garment, electrically heated garment with an aerogel layer and chemically heated insole) were studied in different cold environments. The results showed that the ambient temperature had no significant effect on the insulation of the garment, while increased air velocity significantly reduced the insulation of the garment. Electric heaters were also used in the construction of sleeping bags to improve thermal comfort for the feet and allow eight hours of comfortable sleep in the cold environment studied [6]. Wu et al. [7] have developed a smart heating garment for elderly women that uses a carbon heating film and can automatically adjust the microclimate to different thermal conditions. Older people's ability to regulate their body temperature decreases with age and they are more prone to thermal discomfort in a cold environment. The difference between them and paraplegics is that older people still perceive the warmth of the lower extremities, whereas paraplegics do not. A study conducted by Feng Q. and Hui [8] on the clothing needs of wheelchair users has shown that there is no developed smart garment to improve the thermal comfort of the lower extremities of paraplegics.

The thermal insulation of garments can be determined with the help of the thermal manikin. The early thermal manikins are static and standing, which provides only limited information. Therefore, they were developed with joints that allow the manikin to move. The dry manikin can measure the thermal insulation of clothing, while a sweating manikin can provide more valuable information about heat transfer through evaporation [9–11]. Research into the thermal insulation of clothing with thermal manikins is particularly important for protective clothing to ensure adequate protection against hazards [10, 12, 13], as well as for testing different types of everyday clothing for cold environments in different environmental conditions, such as down jackets, motorbike jackets [14, 15], or also for clothing systems designed for work in office [16].

The main objective of this part of the research was to develop a test prototype of smart heating trousers, to test the developed smart heating system and the thermal insulation of the prototype smart heating trousers using the thermal manikin.

METHODOLOGY

The development of the test prototype of smart heating trousers is based on the research presented in the first part of this article. It provides insights into the thermoregulation of the lower limbs of paraplegics and proposes the design of smart heating trousers based on the results of an extensive survey of paraplegics and a literature review of the clothing requirements and needs of paraplegics.

Development of the test prototype of smart heating trousers

The design of the smart heating system in the trousers is based on detecting the temperature of the microclimate in the left and right trouser leg and automatically regulating the temperature in the left and right trouser leg to the maximum allowable temperature for the safety of the user. It is integrated into the design of the paraplegic trousers and manages the smart heating system via a Bluetooth application.

The pattern design of the prototype of the smart heating trousers was developed based on the four categories of requirements studied (fit and comfort, textile materials, safety, and special requirements) and presented in the first part of this article. In addition, the size of the smart heating trousers was adapted to the dimensions of the male thermal manikin to be able to carry out tests on the thermal insulation of the trousers.

The softshell fabric used to make a test prototype of the smart heating trousers has a surface weight of 346.37 gm^{-2} and a thickness of 1.826 mm. This textile material itself provides good thermal insulation. It is waterproof, windproof, highly breathable, soft, and high-performing.

Testing the prototype of smart heating trousers

To measure the temperature and heat flow for the nineteen segments under constant test conditions, a thermal manikin was used, keeping the temperature of all nineteen segments of the manikin constant according to the standard ISO 15831 [17–19].

This thermal manikin heats all nineteen segments from standard environmental temperature to a fixed temperature of 36 °C. Therefore, for testing the designed smart heating system, the maximum allowable microclimate temperature of the smart heating trousers was set at 36.5 °C. The temperature and heat flow were then measured. The thermal resistance of an individual segment of the manikin was calculated using the known area of the individual segments. The thermal insulation of the garment for a manikin segment in Clo (1 Clo = 0.155 $K \cdot m^2 \cdot W^{-1}$) is automatically calculated for each of the nineteen segments individually. The thermal insulation results are given for the smart heating trousers (a) without heating and (b) with heating for eight leg segments between the nineteen segments of the manikin (right and left thigh on the front and back, right and left calf on the front and back). During the tests, the thermal manikin was dressed in a T-shirt and a jumper to prevent heat loss. Jeans and trousers are normally worn by paraplegic men. Therefore, a comparison of the thermal insulation of jeans trousers and smart heating trousers was carried out.

The thermal properties of the fabrics for the tested trousers were evaluated using a KES-FB Thermo Labo II. The warm-cool feeling (qmax), the constant thermal conductivity (λ), and the constant thermal resistance (R) were determined.

RESULTS AND DISCUSSION

Test prototype of smart heating trousers

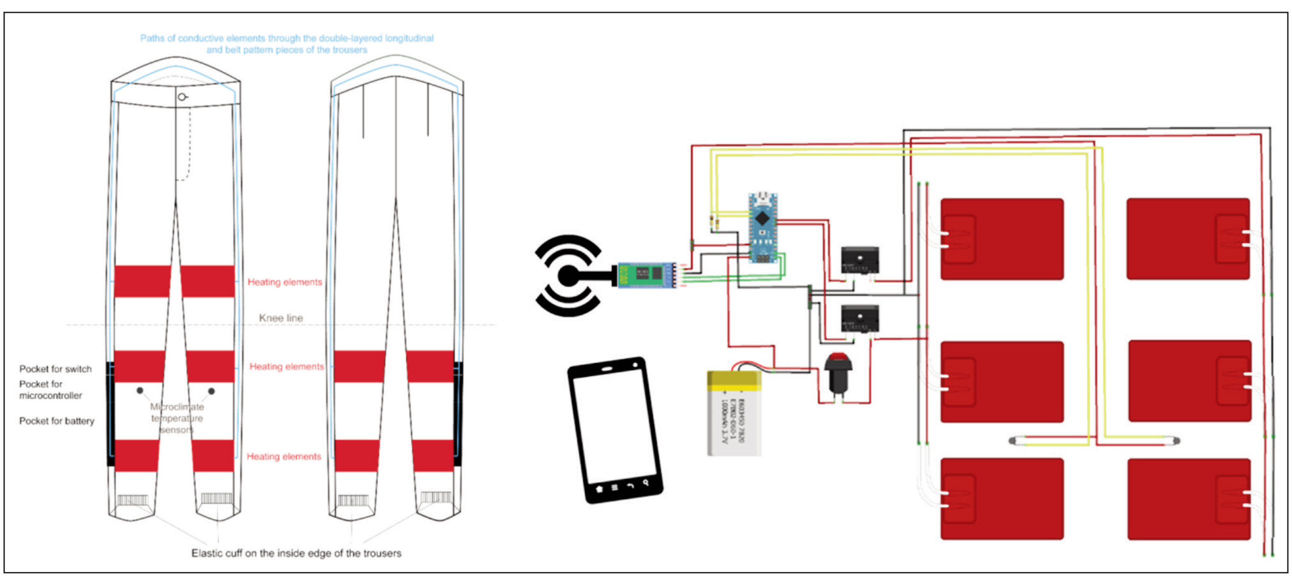
The design of the smart heating trousers was recommended in the first part of the article, figure 1, *a*. The development of the pattern design of the test prototype of smart heating trousers was based on design recommendations and a schematic diagram of the connection of heating elements with electrical components and communication via a Bluetooth connection with a mobile phone, figure 1, *b*, as well as on the dimensions of the heating elements and electrical components. Electric heating pads are one of the most practical and advanced technologies today and can significantly improve thermal comfort. However, their usefulness must be adapted to the specifics of the user to avoid heat damage and burns from the heat. The textile structure of the heating pad is a general form of multi-layer structure in which a conductive material (carbon fibre wire) is sewn inside the two base layers of cotton fabric. When an electric current is applied, the resistivity of the conductive material causes the heating pad to heat up. On the outside of the heating pad is an insulating layer that prevents excessive temperature loss.

The developed trousers have a classic pattern design without pockets and have an extended zip fastening and a waistline adapted to the sitting posture of paraplegics.

During the development process of the trousers pattern, attention was paid to the correct position and insertion of the heating elements in the permissible body areas of the heating, as these must not be located in the areas where the body comes into contact with the wheelchair. At the same time, attention was also paid to the connections of the heating elements and temperature sensors with the microcontroller. Thus, the pattern pieces of the trousers are constructed in such a way that they allow the placement of conductive paths for the connection of the electronic functional blocks.

The heating elements are inserted inside the trousers in two-layer pockets on the thighs above the knees, below the knees and slightly above the ankles, as shown in figure 2, *a*. Temperature sensors are placed below the knee heating elements to measure the microclimate temperature in both trouser legs. The trousers have longitudinal narrow double-layered pattern pieces on the sides of the trouser legs, figure 2, *b*. They are used to route signals to/from the heating elements and temperature sensors through the belt at the back of the trousers to the microcontroller, figure 2, *c*, which detects and processes the signals and automatically regulates the microclimate temperature of the trousers (right trouser leg below the knee). This area also contains a switch to turn the heating on and off and a battery. In this test prototype of the smart heating trousers, the microcontroller, the switch and the battery are placed in pockets on the two-layer pattern pieces on the side of the right trouser leg so that they do not come into contact with the wheelchair, figure 2, *b*. An elastic cuff on the lower inner edges of the trouser legs encloses the ankles and prevents heat from escaping from the trousers.

The development of the smart heating system is based on the application for regulating the temperature of



a *b*

Fig. 1. Design of: *a* – smart heating trousers; *b* – schematic representation of the connection of heating elements with electrical components and communication via a Bluetooth connection with a mobile phone

a *b* *c*

Fig. 2. Details of smart pants: *a* – double-layered pockets inside the trousers on the thighs above the knees, below the knees and above the ankles; *b* and *c* – longitudinal narrow double-layered pattern pieces on the sides of the trousers (right trouser leg – front view and left trouser leg – inside view of double-layered pattern piece)

the microclimate of the trousers, which displays both the real temperature of the environment and the temperature of the microclimate in both trouser legs on the mobile phone. The temperature of the trouser's microclimate is monitored by the microcontroller using NTC (Negative Temperature Coefficient) resistance thermistors. The controller has stored in its memory a program algorithm for processing the input values of the NTC thermistors and regulating the temperature in the trouser legs. The regulation algorithm is performed by comparing the input set temperature and the actual temperature of the heating element in the trousers. We have chosen a PI controller as the control algorithm, as we believe that more accurate algorithms are not necessarily due to the slow temperature response, as shown in figure 3. By setting the PI control constants (Kp – proportional and Ki – integral) the amount of heating power, through voltage, changes depending on the error (the larger the error, the more heating power is supplied to the heating element, the smaller the temperature error, the less heating power is supplied), as shown in equation 1:

$$u(t) = K_p \cdot e(t) + K_i \int_0^t e(\tau)\,d\tau \qquad (1)$$

where $u(t)$ is the controlled variable, which is converted into an electrical variable and indirectly into heating energy, and $e(\tau)$ is the error value as the difference between the desired setpoint $r(t)$ and the measured process variable (from the heating process). K_p and K_i are non-negative coefficients for the proportional and integral terms. In equation 1 we see that the equation depends on time, where the variables t is time or instantaneous time (the present) and t is the integration variable (takes values from time 0 to the present).

The desired maximum temperature of the microclimate in the trousers is set by the software and cannot be changed for safety reasons.

If the error is equal to 0°C, no power is used for heating. Likewise, if the current temperature is greater than or equal to the upper allowable temperature limit, which is checked outside the control loops, heating will not take place. In the first part of this article, it was stated that the highest average skin surface temperature on the leg for a healthy person is 31.7°C, measured in the thermally neutral zone and at rest. Therefore, it can be assumed that the legs of paraplegics can be safely warmed to this skin surface temperature.

At the same time, the temperature measurements are taken separately in both trouser legs, i.e. we implement two regulation loops for the automatic heating of the trousers. Bluetooth communication

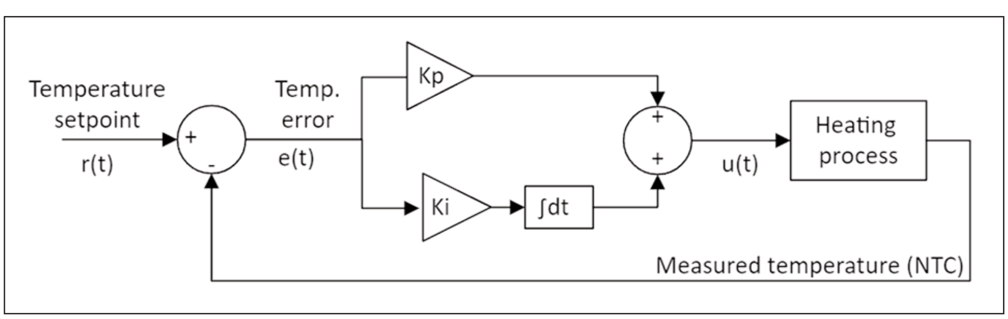


Fig. 3. PI controller for one trouser leg heater

takes place between the mobile phone and the microcontroller built into the trousers to switch the heating of the trousers on or off and to display the current and desired temperature. The complete flow chart of the control algorithm is shown in figure 4.

A test prototype of smart heating trousers with controlled temperature within the trousers microclimate is shown in figure 5. The smart heating system is robust and is used to test the temperature regulation algorithm on the microcontroller, which is connected to the app on the mobile phone via Bluetooth communication, figure 5. The following research activities focus on the development of a textile heating element and the incorporation of miniature electrical components into the trousers, including a battery that enables the smart heating trousers to be worn for up to 5 hours in a cold environment. In addition, a new test prototype of the smart heating trousers will be developed according to the body measurements of the paraplegic. The virtual 3D prototyping process based on a 3D body model of the paraplegic enables precise positioning of the heating elements in the allowed heating areas. An example of a 3D virtual prototyping process of personalised smart heating trousers has been included in the Erasmus+ e-learning materials of the project *OptimTex – Software tools for textile creatives* (2020–2022). The project aimed to improve the knowledge and skills of university students in the field of software applications and increase their employability in textile companies by providing them with adequate training for their profession. Therefore, five e-learning materials were produced as part of this project: Design and Modelling of Woven Structures, Design and Modelling of Knitted Structures, Design and Modelling of Garments through 3D Scanning Software and CAD/PDS Software, Design and Modelling of Embroidered Structures and Software for Experimental Design [20]. The realisation that 3D technologies are becoming increasingly important in the fashion world has led to the new Erasmus+ project *DigitalFashion – Collaborative Online International Learning (COIL) in Digital Fashion* (2022–2025) [21]. It aims to build an educational platform for fashion design through personalised 3D virtual garment customisation and to design curricula for COIL digitally based on the new methodology for a common framework on COIL and a knowledge library (the three databases) for virtual fashion design and technology [22, 23]. The DigitalFashion project is already the

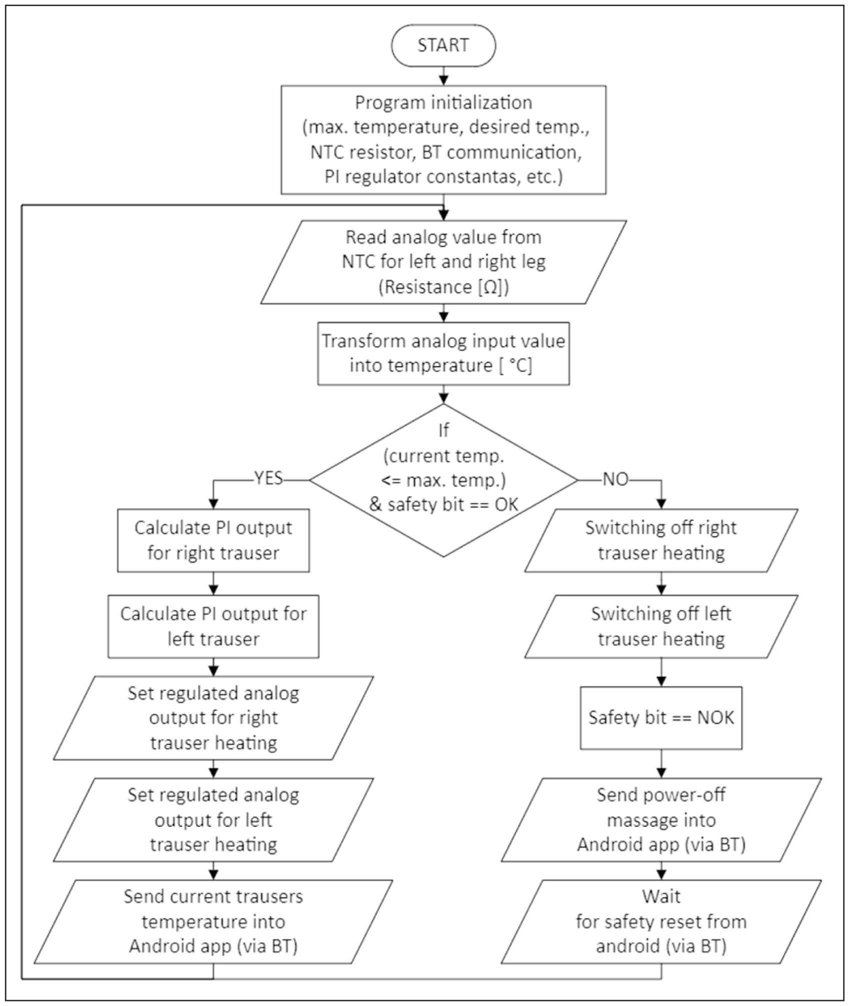


Fig. 4. Control algorithm flow diagram

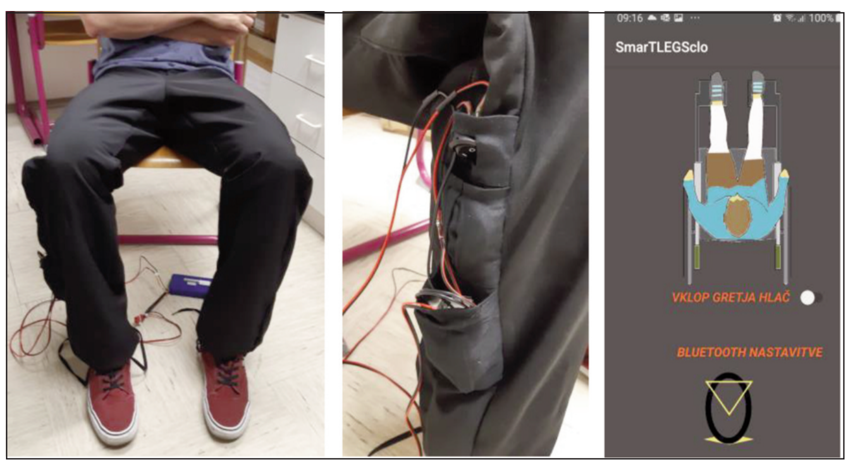


Fig. 5. A test prototype of smart heating trousers and an app on the mobile phone

next and fifth successful project dedicated to e-learning in the wider textile sector (Advan2Tex, TexMatrix, Skills4Smartex, OptimTex). The projects were carried out by a consortium of universities and institutes from European countries, coordinated by the National Research and Development Institute for Textiles and Leather, INCDTP – Romania.

Results on the thermal insulation of smart heating trousers prototype

The results of the measurement of the thermal properties of trousers fabrics obtained with the Thermo Labo II measuring system show better thermal insulation of the softshell fabric compared to the jeans fabric, based on the measured warm-cool feeling, constant thermal conductivity and constant thermal resistance.

The softshell fabric used for the smart heating trousers has a warm-cool feeling of 0.203 W/cm^2, a constant thermal conductivity of 0.045 W/mK and a constant thermal resistance of 0.040 m^{2}K/W. The jeans fabric has a warm-cool feeling of 0.176 W/cm^2, a constant thermal conductivity of 0.073 W/mK and a constant thermal resistance of 0.0138 m^{2}K/W.

The results of the thermal insulation in Clo for the smart heating trousers, measured with and without heating, and for the jeans trousers are shown in figure 6 for the eight leg segments of the thermal manikin (right and left thigh on the front and back, right and left calf on the front and back). As we expected, the thermal insulation of jeans trousers is lower than that of trousers made of softshell fabric. By setting up a smart heating system in the trousers, the thermal insulation was increased and the heating system was set up in both trouser legs.

Future research with the thermal manikin will focus on the controlled regulation of the lower extremity skin surface temperature of the thermal manikin set to the average lower extremity skin surface temperatures studied in the first part of this research. In this way, we will be able to accurately monitor the effectiveness of the trousers' thermal insulation and predict the thermal comfort of wheelchair users' legs under different environmental conditions (temperature, air velocity) with the developed smart heating trousers.

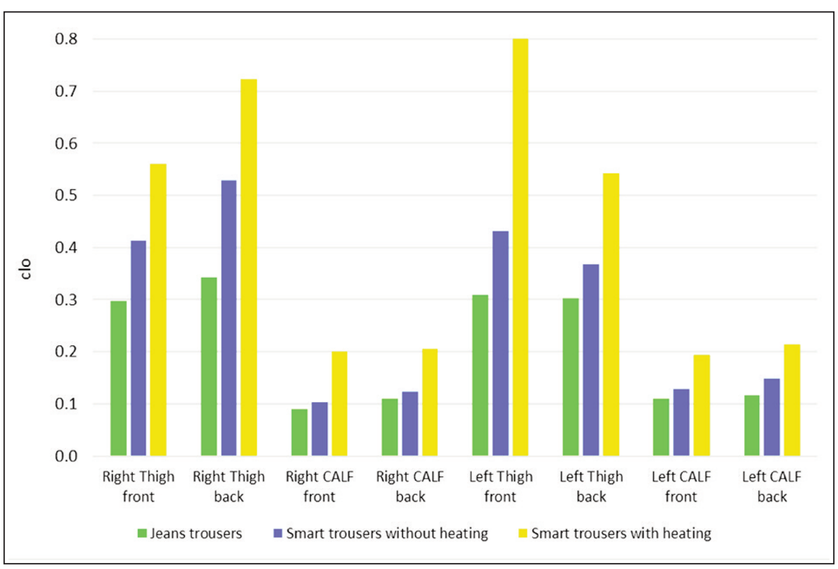


Fig. 6. Clo values of the trousers on the segments of the thermal manikin

CONCLUSIONS

Clothing is important to protect the human body from exposure to cold. This is especially important for paraplegics who cannot feel the temperature of their legs. Wearing smart heating clothing can increase the time wheelchair users spend in a cold environment and therefore reduce the risk of cold injuries. The research presented has shown that the use of smart heating trousers can improve the thermal insulation of the legs. The smart technology in the trousers provides heating of the microclimate in the leg area when the paraplegic is exposed to a cold environment for a prolonged period, which is ensured by a carefully planned and safe algorithm. The proposed smart heating system allows automatic regulation of the temperature of the trousers' microclimate, which switches off when the maximum allowable temperature is reached. The next step in our research is to test the dependency between the different environmental conditions and the temperature of the trousers microclimate, as well as the heating time interval of the developed smart trousers on the thermal manikin.

ACKNOWLEDGEMENTS

The authors would like to express their deepest gratitude to all those who participated in the research.

We thank the Laboratory for Intelligent Manufacturing Systems at the Mechanical Engineering Research Institute, Faculty of Mechanical Engineering, University of Maribor, for performing the measurements on the thermal manikin.

FUNDING

The research was partially supported financially by the European Union through the European Social Fund and Slovenian Ministry of Education, Contract number: 11081-24/2018, the Slovenian Research Agency (Research Programme P2-0123: Clothing Science, Comfort and Textile Materials), the EC Programme Erasmus+, project OptimTex, project No. 2020-1-RO01-KA203-079823 and the project of EC Programme Erasmus+, project DigitalFashion, project No. 2021-1-RO01-KA220-HED-000031150.

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