Investigations for the development of smart trousers for paraplegic wheelchair users. Part 1 – Design recommendations for smart trousers to improve the thermal comfort of the legs of paraplegics

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ANDREJA RUDOLF
VANJA KOLANOVIČ
MONIKA HUDOURNIK
JASNA ŠTAMPFER
JAKOB NOVAK
MATEJ BOROVEC
ROK BELŠAK

ABSTRACT – REZUMAT

Investigations for the development of smart trousers for paraplegic wheelchair users. Part 1 – Design recommendations for smart trousers to improve the thermal comfort of the legs of paraplegics

In this article, a study was conducted on the design of smart trousers to improve the thermal comfort of the legs of paraplegics. It was based on the survey of paraplegics about the thermoregulation of their legs in cold environments, the warming of the legs during and after outdoor activities, the type of clothing for outdoor activities and the need for smart heating clothing for the lower extremities. The skin surface temperatures on the legs of fully mobile people and paraplegics were measured in a neutral state to find out to which temperature the microclimate inside the trousers can be warmed and the smart trousers can be used safely. The survey of paraplegics was conducted nationwide and included sixty-one adult male and female subjects. Skin surface temperatures were measured at eight measurement points on the right and left leg and performed on eighteen participants. After evaluating all the results of this study, recommendations for the design of smart heating trousers were proposed. The results of this part of the research can provide designers with important information about the specific requirements for smart heating trousers and enable them to design and develop products that meet real needs and are safe for paraplegic wheelchair users. Furthermore, this work aims to raise awareness of the needs of wheelchair users that enable them to integrate into the social environment on an equal footing.

Keywords: *paraplegics, cold protection, thermal comfort, legs skin surface temperature, smart heating trousers design*

Investigații pentru dezvoltarea pantalonilor inteligenți pentru utilizatorii cu paraplegie în scaune cu rotile. Partea 1 – Recomandări de proiectare pentru pantaloni inteligenți pentru a îmbunătăți confortul termic al picioarelor persoanelor cu paraplegie

În acest articol, a fost realizat un studiu despre designul pantalonilor inteligenți pentru a îmbunătăți confortul termic al picioarelor persoanelor cu paraplegie. Studiul s-a bazat pe sondajul efectuat persoanelor cu paraplegie despre termoreglarea picioarelor în medii reci, încălzirea picioarelor în timpul și după activitățile în aer liber, tipul de îmbrăcăminte pentru activități în aer liber și necesitatea îmbrăcămintei inteligente cu încălzire pentru extremitățile inferioare. Temperaturile suprafeței pielii picioarelor persoanelor complet mobile și ale persoanelor cu paraplegie au fost măsurate în stare neutră pentru a afla până la ce temperatură poate fi încălzit microclimatul din interiorul pantalonilor, iar pantalonii inteligenţi să poată fi utilizaţi în siguranță. Sondajul pentru persoanele cu paraplegie a fost realizat la nivel național și a inclus 61 de subiecți adulți, bărbați și femei. Temperaturile suprafeței pielii au fost măsurate în opt puncte de măsurare pe piciorul drept și stâng și efectuate pe optsprezece participanți. După evaluarea tuturor rezultatelor acestui studiu, au fost propuse recomandări pentru proiectarea pantalonilor inteligenţi cu încălzire. Rezultatele acestei părți a studiului pot oferi designerilor informații importante despre cerințele specifice pentru pantalonii inteligenţi cu încălzire și le permit să proiecteze și să dezvolte produse care răspund nevoilor reale și sunt sigure pentru utilizatorii cu paraplegie ai scaunelor cu rotile. În plus, această activitate urmărește să crească gradul de conștientizare cu privire la nevoile utilizatorilor de scaune cu rotile care să le permită să se integreze în mediul social în mod egal.

Cuvinte-cheie: *persoane cu paraplegie, protecție împotriva frigului, confort termic, temperatura suprafeței pielii picioarelor, design inteligent al pantalonilor cu încălzire*

INTRODUCTION

Human thermal comfort has been defined as a state of mind that illustrates satisfaction with the thermal environment. Thermal comfort is related to the thermal balance between the human body and the thermal comfort of its environment [1, 2]. Exposure to cold can lead to cold injuries, which are divided into freezing and non-freezing injuries. Freezing cold injuries occur because the temperature is lowered by cooling to such an extent that the tissue fluid freezes. Non-freezing cold injuries occur when blood flow is reduced after cooling and the low temperature causes nerve damage. Less severe injuries include cracked skin and frostbite or itchy swellings on the skin, typically on the hand or foot, nose or ears, caused by poor blood flow to the skin when exposed to cold [3–5].

With smart garments, it is possible to protect people from cold stress and put them in a thermally neutral or comfortable state. Three basic types of heating garments are known: electric heating garments with embedded heating elements, heating garments with phase change materials (PCM) that store and release large amounts of energy by changing the solid-liquid state, and chemical heating garments that use a reaction of chemical substances to generate heat [5].

This paper focuses on the design of smart trousers for a paraplegic wheelchair user. They are restricted in the movement of their lower limbs due to spinal cord injuries and often face other health problems such as incontinence, chronic urinary tract infections, skin irritation and inflammation, pressure ulcers, cardiovascular complications, frequent colds, poor blood circulation to the lower limbs and hence body temperature regulation and hypothermia of the lower limbs [6–8]. Previous research has shown that paraplegics are extremely careful to avoid hypothermia in their lower limbs. They try to regulate the temperature of the lower limbs when it is cold by choosing warm clothing, covering the legs with a blanket and keeping an eye on the duration of outdoor activities [8, 9]. Feng and Hui [10] conducted a systematic literature review on the clothing needs of wheelchair users. They found eight main characteristics related to the clothing needs of wheelchair users: functional needs, appropriate textile materials, safety aspects of clothing patterns, aesthetic and expressive needs, quality of life and extrinsic attributes, reflecting two general groups, the physical and psychological needs of wheelchair users. None of the research addresses smart clothing to protect the health and prevent additional injuries of wheelchair users.

The body temperature of a healthy person is very stable under normal conditions. It is usually measured orally and reflects the temperature of the blood [11–13]. The normal oral temperature measured in a large population ranges from 36.5°C to 36.9°C [12, 13], and the range of this interval is quite similar in many other studies. People with spinal cord injuries may have impaired regulation of body temperature or a poorer response to environmental changes. People with high-level spinal cord injuries may be particularly insensitive to changes in heat or cold, most likely due to loss of hypothalamic control, poor vasomotor responses, or other unknown factors [13]. Basically, in a hot environment, the body normally sends an overheating signal from the brain to the spinal cord. Then overheating is prevented by instructing the body to cool itself by sweating. In a cold environment, the brain sends the signal for the blood vessels to constrict to prevent hypothermia and signals us to dress warmer. Paraplegics have no sensation in the lower limbs (below the lesion) and cannot send these signals properly, so the body experiences hyperthermia (heat) or hypothermia (cold) [14]. In a study by Khan S. et al. [13], subnormal body temperature (35°C) was found to be very common in people with chronic spinal cord injury (66%), and a critically low temperature in the hypothermic range (<35°C) requiring therapeutic intervention was found in 3% of measurements.

When the skin temperatures of ten body segments of fully mobile subjects (forehead, upper arm, forearm, back of the hand, chest, thigh, anterior calf, posterior calf, instep of the foot) were examined at an air temperature of 20°C to 30°C at a rate of 1°C, the skin temperatures for the thigh were 32.0°C, the anterior calf 31.1°C, the posterior calf 30.2°C and the instep of the foot 30.3°C at an air temperature of about 25°C [15]. A study by Kingma et al. [16] analysed combinations of core body temperature (Tc), skin temperature (Ts), and ambient temperature (Ta) that correspond to the biophysical requirements of the thermoneutral zone (TNZ) in humans. The TNZ is defined as the range of ambient temperature in which the body can maintain its core temperature alone and in which heat production and heat loss are balanced [16]. It has been found that the TNZ for a clothed person is in the Ta range of 14.8°C – 24.5°C when the Ts range is between 28.8°C and 36.4°C and the Tc range is between 36°C and 38° [16]. Trbovich [17] investigated that the mean skin temperature at rest at neutral ambient temperature (20°C) in healthy (31.7°C) and spinal cord injured participants (31.4°C) and in participants with paraplegia (29.5°C) and tetraplegia (30.6°C) were similar, while in paraplegic individuals the skin temperatures at the thigh (30.3°C) and calf (29.0°C) were lower than in healthy individuals (thigh – 31.6°C; calf – 31.7°C).

Maintaining physical condition is the main activity of a paraplegic wheelchair user, using outdoor activities [18]. In windy, damp and cold weather, their integration into the social environment is hampered. To reduce the risk of cold injuries, wearing smart heating clothing can increase the time wheelchair users spend in a cold environment.

There are no special smart heating trousers on the world market that are suitable and safe for wheelchair users. The reasons for this are: (a) paraplegic wheelchair users have no feeling of warmth in their legs, (b) the design of the trousers must be adapted to the sitting posture [19] and (c) the constant contact of the buttocks, hips and thighs (back) with the wheelchair. The heating trousers on the market can cause additional health problems for paraplegic wheelchair users. Heating pads in the area of the buttocks or hips in contact with the wheelchair can in fact cause sweating and inflammation of the skin as well as pressure sores, as we can see from the examples [20, 21]. The electric heating pads available on the market can be easily integrated into clothing. They are washable, produce a maximum temperature of 65°C and should not be used by people who are not sensitive enough to heat [22]. What all the heating garments presented here have in common is that we can choose the temperature of the heating elements ourselves, which is not without danger for paraplegics.

The main objective of this research was to: (1) identify the problems of paraplegic wheelchair users with thermoregulation of their legs and their needs in terms of developing smart heating trousers to maintain the thermoneutral status of paraplegics in cold outdoor conditions by surveying paraplegics, (2) investigate the skin surface temperature of the legs of fully mobile persons and wheelchair users to find out temperature to which the microclimate within the trousers can be heated so that the smart heating trousers can be used safely; and (3) present design recommendations for smart heating trousers that will enable paraplegics to use them safely on a controlled temperature basis within the trouser microclimate.

METHODOLOGY

Survey

A survey was conducted among the members of the Slovenian Paraplegic Association. The questionnaire was divided into three groups in addition to the basic questions: (1) thermoregulation of the lower extremities and garments commonly used to warm the legs outdoors, (2) need for smart heating garments and specific desires to control them, and (3) other functional characteristics of smart heating garments. The questionnaire was answered anonymously and contained different types of questions: demographic questions, dichotomous questions, multiple choice questions and open questions to get the best possible opinion on smart heating garment design. The questionnaire was analysed using descriptive statistics, as the main purpose was to get a clear need and idea about smart heating garment design.

Measurements of the skin surface temperatures on the legs

To assess the ability of the lower extremities to thermoregulate, measurements of the surface skin temperatures on the legs of the two groups, healthy fully mobile individuals and paraplegic individuals, in continuation Fully Mobile Individuals (FMI) and Immobile Individuals (IMI), were made using a FLIR thermal camera. The locations of the measurements were based on the results of the questionnaire.

Participants and measurements

Measurements were taken on 18 volunteer participants, 10 FMI and 8 IMI. A total of fourteen men (7 FMI, 7 IMI) and four women (3 FMI, 1 IMI) participated in both groups. The basic data of the measured individuals are listed in table 1.

Skin surface temperatures were measured at eight measurement points on both the right leg (RL) and the left leg (LL): T1 – middle of the anterior midline of the thigh; T2 – lateral lower thigh above the knee; T3 – middle of the front of the knee; T4 – middle of the anterior midline of the tibia; T5 – middle of the lateral line of the tibia; T6 – ankle lateral; T7 – middle part of the instep; T8 – thumb. The subjects' measurements were taken at rest, sitting in a wheelchair or chair, at a daytime temperature of 24°C ± 1°C and relative humidity of 50% ± 2.5%, wearing shorts and a T-shirt. This daytime temperature provided a thermoneutral environment [16] during the measurements. All participants were informed in advance about the research purposes and the requirements for the measurements and had the opportunity to discuss these before giving their consent to participate.

Data Analysis

Average values ($\bar{x}$), standard deviations (SD) and coefficients of variation (CV) of the skin surface temperatures measured at eight points on the legs were calculated. The differences between the average values of the skin surface temperatures of RL and LL were calculated for FMI and IMI and between FMI and IMI for both legs.

Design recommendations for smart heating trousers

After reviewing all the data collected in this study as well as literature studies, recommendations for the design of smart heating trousers were proposed. The requirements for smart heating trousers for paraplegic wheelchair users were divided into four different groups, summarised by source [23]: (a) fit and comfort, (b) textile materials, (c) safety and (d) special requests.

RESULTS AND DISCUSSION

Results of the survey

Sixty-one paraplegics, both men (70%) and women (28%), who using a wheelchair for an average of 19.6 years, answered the questionnaire (no response 1%). The survey was mainly attended by paraplegics over 41 years of age: age group 18–20 years (3%), 21–30 years (5%), 31–40 years (13%), 41–50 years (25%), 51–60 years (28%) and over 60 years (26%).

Table 1

BASIC DATA OF THE INDIVIDUALS MEASURED

IMI				FMI			
Age (years)	**Height (cm)**	**Weight (kg)**	**BMI**	**Age (years)**	**Height (cm)**	**Weight (kg)**	**BMI**
Male (mean ± SD)				Male (mean ± SD)			
51.71 ± 10.32	174.86 ± 3.44	84.14 ± 7.95	27.48 ± 1.88	25.50 ± 10.76	181.20 ± 12.48	78.80 ± 16.67	23.67 ± 3.39
Female (mean ± SD)				Female (mean ± SD)			
54.00 ± 0.00	170.00 ± 0.00	50.00 ± 0.00	17.30 ± 0.00	21.33 ± 2.08	164.33 ± 5.13	65.67 ± 13.43	25.65 ± 5.25

Lower limb thermoregulation and garments to warm the legs outdoors

The paraplegic wheelchair users predominantly estimate the warmth of their legs as chilly – fairly cold (39%) and cool – slightly cold (31%). Some of them estimate that their legs are usually icy – very cold (11%) and some that they are warm (13%), while of the 5% of respondents, their legs are icy in winter and the feeling of their legs depends on the temperature and their legs cool down very quickly. Problems with hypothermia were already experienced by 25% of the paraplegic respondents.

When asked what kind of leg protection they use, most respondents answered with a blanket (41%) and only 8% with a heating leg bag. A surprisingly high percentage of paraplegics do not use leg protection (34%). This is consistent with the responses to the open-ended questions that some of them prefer to wear two pairs of trousers or warm functional ski underwear under their trousers. They also prefer warm functional socks (36%) and gaiters (25%).

The answers clearly show that paraplegic wheelchair users want to warm their feet (72%), knees (64%), ankles (64%), shins (52%), and thighs (26%). The open response on the parts of the body that should not be warmed revealed that these are the buttocks, abdomen, crotch and the parts of the hips and thighs that come into contact with the wheelchair.

Needs for smart heating garment and particular desires for its control

Of the sixty-one paraplegic wheelchair users, almost all respondents (98%) expressed a desire for a smart garment that warms their legs. They would feel safer if the smart heating garment measured the temperature of their legs and displayed it on their smartphone (89%), as well as the outside temperature (69%). They would like to control the smart heating garment with their smartphone (66%), with buttons integrated into the garment (23%), with a touch screen attached to the wheelchair (10%), and with a wristband on their hand (1%).

The results show how strong the desire for outdoor social contact is among wheelchair users. With smart heating garments, they would like to go for a long walk (84%), participate in social (62%) and sporting events (56%) and have a chat over a coffee outside (61%). 46% of respondents would like to do their outdoor activities between 1 and 3 hours and 38% between 3 and 5 hours.

The desire for a specific smart heating garment and its' functional properties

Respondents were asked what type of smart heating garment they would prefer to wear. 41% of the respondents answered that they would like smart heating trousers in the classic trousers pattern design, while 25% of the paraplegics prefer sports trousers, only 7% skinny trousers and 5% others (jeans, custom-made). The paraplegics expressed that the smart heating garment should above all be easy to put on (90%), windproof (82%), waterproof (70%) and have an aesthetic appearance (46%). Under the trousers, they wear ski underwear (36%), stockings (33%), and leggings (18%) in a cold environment. They want the trousers to close with a zip (57%), Velcro (15%), buttons (13%), snaps (2%) and others (11% – elastic band). They predominantly (90%) want trousers in neutral colours and less in bright colours.

From the results of the survey, it can be concluded that paraplegic wheelchair users would like to have smart heating trousers that only warm the front of the thighs and the entire knee, shin and ankle area for a period of 1 to 5 hours during outdoor activities. They would feel safer if the smart heating trousers measured and displayed the temperature of their legs and the outside temperature. They would like the smart heating trousers to be controllable via a smartphone. In addition, the trousers should have a classic pattern design, be made of windproof and waterproof textile material in neutral colours, have a zip, be easy to put on and look aesthetically pleasing.

Skin surface temperatures on the legs

The results of the measured skin surface temperatures of the legs under thermoneutral environmental conditions at the eight temperature measurement points (T1 – T8) on the right leg (RL) and left leg (LL) for FMI and IMI are summarised in table 2.

The average skin surface temperatures at the measured points on the legs vary between 28.31°C (T8-LL) and 32.70°C (T5-LL) for FMI and between 26.31°C (T8-RL) and 29.00°C (T6-LL) for IMI. The lowest skin surface temperature is measured at the thumb (T8) for both FMI and IMI. For both FMI and IMI, there are large differences between T8 for the individuals measured, as the CV for FMI is 18.25% (RL) and 16.57% (LL) and for IMI the CV is 12.76% (RL) and 14.86% (LL). The comparison of skin surface temperatures between the right and left legs in figure 1 shows that the temperatures between the right and left legs are not as different for FMI as they are for IMI. The average difference in skin surface temperature between the left and right leg is 0.02°C for FMI and 0.5°C on average for IMI and is higher for the left leg, table 3.

The comparison of skin surface temperatures between FMI and IMI for the right and left leg shows a clear difference in the measured temperatures, which are higher for FMI, but their trend at the measurement points is similar, figure 2. The difference in skin surface temperature of the right leg between FMI and IMI ranges from 1.96°C (T6) to 4.40°C (T5) and for the left leg from 0.81°C (T8) to 3.84°C (T5), table 3. The average skin surface temperature of the right leg is 3.31°C higher for FMI compared to IMI and for the left leg, it is 2.79°C higher for FMI compared to IMI, table 3.

The measured skin surface temperatures on the legs and the results of this study are in agreement with the results of the studies [15, 17]. In the study of [24], skin surface temperature (SST) was measured on the 12 body regions (from the head to the sole of the foot) of 30 healthy individuals at a constant temperature and humidity of 24.4°C ± 1.1°C and

Table 2

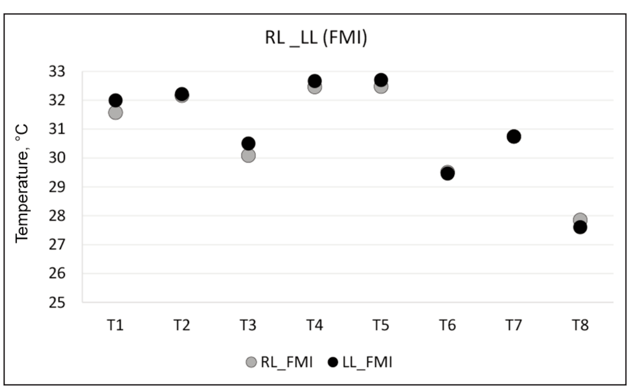
MEASUREMENTS OF SKIN SURFACE TEMPERATURES ON THE LEGS OF FMI AND IMI												
Measurement location on RL and LL	**Measurements of the leg's skin surface temperatures**											
	RL_FMI			**LL_FMI**			**RL_IMI**			**LL_IMI**		
	(°C)	SD(°C)	CV(%)	(°C)	SD(°C)	CV(%)	(°C)	SD(°C)	CV(%)	(°C)	SD(°C)	CV(%)
T1 – Middle of the anterior midline of the thigh	31.76	1.15	3.61	32.24	1.40	4.38	28.50	1.87	6.56	28.99	1.51	5.21
T2 – Lateral lower thigh above the knee	32.32	1.38	4.26	32.24	1.36	4.21	28.63	2.34	8.18	28.70	1.91	6.64
T3 – Middle of the front of the knee	30.30	2.51	8.3	30.70	2.42	7.88	26.71	2.52	9.43	27.17	2.96	10.90
T4 – Middle of the anterior midline of the tibia	32.60	0.87	2.66	32.57	0.87	2.66	28.74	1.94	6.76	28.77	2.15	7.46
T5 – Middle of the lateral line of the tibia	32.63	0.90	2.76	32.70	0.89	2.73	28.23	2.04	7.22	28.86	2.08	7.22
T6 – Ankle lateral	30.06	2.64	8.79	30.08	2.9	9.63	28.10	2.79	9.94	29.00	2.33	8.05
T7 – Middle part of the instep	31.67	1.96	6.20	31.32	1.61	5.15	28.37	2.76	9.73	28.67	3.20	11.18
T8 – Thumb	28.73	5.24	18.25	28.31	4.69	16.57	26.31	3.36	12.76	27.50	4.09	14.86

Table 3

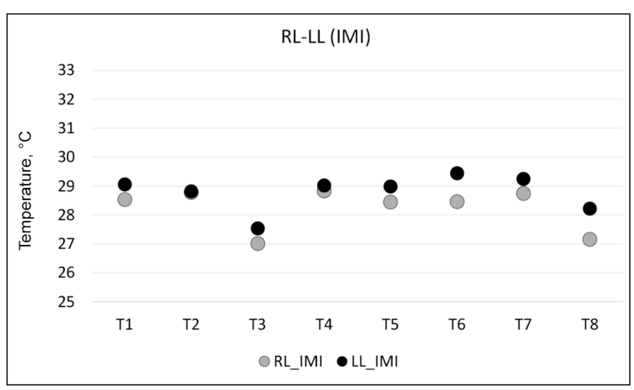
DIFFERENCES (D) BETWEEN THE MEAN VALUES OF RL AND LL SKIN SURFACE TEMPERATURES AND BETWEEN FMI AND IMI				
Measurement location on RL and LL	**Differences in the leg's skin surface temperatures (°C)**			
	D_{RL-LL}**FMI***	D_{RL-LL}**IMI***	**DRL**$_{FMI-IMI}$	**DLL**$_{FMI-IMI}$
T1 – Middle of the anterior midline of the thigh	– 0.29	– 0.49	3.26	3.06
T2 – Lateral lower thigh	0.08	– 0.07	3.69	3.54
T3 – Middle of the front of the knee	– 0.40	– 0.46	3.59	3.53
T4 – Middle of the anterior midline of the tibia	– 0.20	0.03	3.86	3.80
T5 – Middle of the lateral line of the tibia	– 0.07	– 0.63	4.40	3.84
T6 – Ankle lateral	– 0.02	– 0.90	1.96	1.08
T7 – Middle part of the instep	0.34	– 0.30	3.30	2.65
T8 – Thumb	0.42	– 1.19	2.42	0.81
Average difference	– 0.02	– 0.50	3.31	2.79

Note: *A negative value means higher skin temperature of the left leg compared to the right leg.

46.3% ± 6.5%. This study found the highest SST of 35.0°C ± 0.5°C for the front of the neck, the thigh of 31.9°C ± 0.7°C and the lowest SST of 29.8°C ± 1.6°C for the sole of the left foot. The measurement conditions and results of this study for the SST of the legs agree quite well with our results for the FMI.

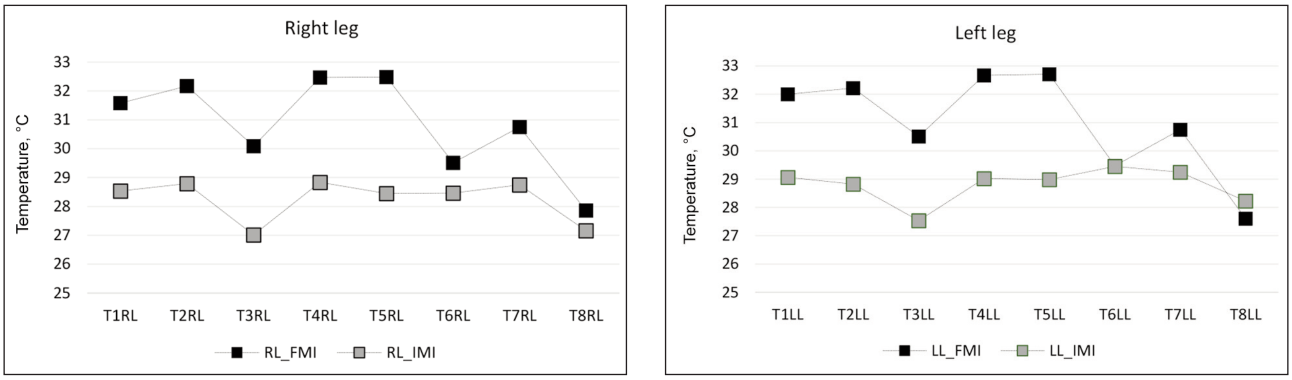


a



b

Fig. 1. Comparison of skin temperatures between the right and left leg for: *a* – FMI; *b* – IMI



a *b*

Fig. 2. Comparison of skin surface temperatures between FMI and IMI for: *a* – the right leg; *b* – the left leg

The results obtained indicate that it is necessary to bring the skin temperature of paraplegics closer to that of a fully mobile person by regulating the microclimate of the garment.

Garments create a specific microclimate around the body that depends on the thermal state of the person, the environmental conditions and the characteristics of the garment. The temperature of the microclimate in clothing refers to the layer of air closest to the skin when people wear garments [25] and depends on many factors, such as the humidity and temperature under the clothing and the carbon dioxide under the clothing [26]. Under environmental conditions within the comfort range, it has been studied that the temperature of the innermost layer of the garment could have a greater impact on the comfort of wearing a particular garment than the temperature of the microclimate [25]. In this study, the temperature of the innermost layer of the garment was found to be slightly lower than the skin temperature.

The average skin surface temperature on the legs (T1-T6) without measurements on the foot (T7-T8) is 31.61°C for the right leg and 31.72°C for the left leg of FMI, i.e. 3.46°C higher for the right leg and 3.14°C higher for the left leg compared to IMI. Based on the results of this part of the study and the review of other studies, we can assume that the legs of paraplegics can be safely warmed to a skin surface temperature of 31.7°C. In the future, further research is needed on the relationship between the temperature of the inner layer of the smart heating garment, the skin surface temperature, and the thermal comfort of paraplegics to ensure the highest level of safety when wearing the smart heating garment.

Design recommendations for smart heating trousers

The design of well-fitting, comfortable and functional garments should take into account the interaction between garment design and the characteristics of the human body, i.e. anatomical, physiological and psychological needs and desires.

Based on the results, the proposed design recommendations related to the different problems, needs and desires of paraplegics were classified into four groups, which are briefly explained in table 4. The design of the smart heating trousers is shown in figure 3, after which the prototype was developed and tested, the results of which will be presented in Part 2 of this article.

Fit and comfort

Adaptation of trousers to a sitting posture

Due to the sitting posture of paraplegics in wheelchairs, the smart heating trousers must be ergonomically adapted to the sitting posture and body measurements of the person. This is the only way to achieve a perfect fit and comfort in the trousers and to prevent possible additional health problems for paraplegics [19, 27].

(1) The trousers must be constructed according to the body measurements of the paraplegic in a sitting posture.

(2) To prevent the trousers from wrinkling below the waist and being uncomfortable and unaesthetic when sitting, the trousers should be designed lower at the front and higher at the back in the lumbar region to increase comfort and reduce possible health problems caused by an open lumbar region.

(3) Shifting the knee line to a seated posture prevents the trousers from putting pressure on the thighs.

(4) Lengthening the trouser legs is necessary because of the seated posture.

(5) Trousers should not be too tight and exert excessive pressure on the body, hindering blood circulation. On the other hand, they should not be too wide either, as this can cause skin irritation on the buttocks and hips due to wrinkling.

(6) Classic pockets on the front and back of the trousers can put excessive pressure on the body.

(7) All seams of the trousers, especially those in contact with the body, must be sewn as flat as possible to avoid friction and irritation of the skin of the paraplegic.

Easy dressing

The results of this and previous surveys have shown that one of the biggest functional requirements for trousers is to be easy to dress.

(1) The type of trouser fastening used by paraplegics is a zip, which can be slightly longer than in normal

Table 4

RECOMMENDATIONS FOR THE DESIGN OF SMART HEATING TROUSERS FOR PARAPLEGICS	
Problems and needs of paraplegics	**Recommendations for the design of smart heating trousers**
Fit and Comfort	
Adaptation of trousers to a sitting posture	1 – Body measurements 2 – Adjustment of trouser waistline to a sitting posture 3 – Shifting of knee line to a sitting posture 4 – Lengthening of trouser legs 5 – Adjustment of trousers width 6 – Without pockets 7 – Seams
Easy dressing	1 – Zip fastening 2 – Elastic waistband 3 – Aids for dressing
Other	1 – Easy handling of the urine bag 2 – Thermal insulation
Textile materials	
Functional textile materials	1 – Durable and soft textiles 2 – Good thermal insulation 3 – Waterproof and windproof 4 – Highly breathable
Safety	
Trousers heating areas	1 – The permitted areas of heating
Controlled regulation of the temperature of the microclimate in the trouser	1 – Maximum microclimate temperature 2 – Microclimate temperature sensors 3 – Automatic shutdown of heating 4 – Turning on the heating 5 – Application for temperature regulation 6 – Position of switch, microcontroller, and battery
Special desires	
Trousers appearance	1 – Classic pattern design 2 – Neutral colours 3 – Aesthetic appearance
Use	1 – Outdoor activities 2 – Care

trousers to create more volume and make the trousers easier to pull onto the body.

(2) The use of an elastic band at the waist helps to easier dressing and improves the fit and comfort of the trousers.

(3) Dressing aids in the form of sewn-in longer inner loops at the back of the trousers at the waist can assist paraplegics in pulling the trousers onto the body.

Other

(1) Due to urinary incontinence, some paraplegics need to use a urine bag, which is usually worn on the calf. It is therefore necessary to adjust the width of the trouser leg on the side of the urine bag and discreetly insert a hidden zip in the seam to facilitate changing the urine bag.

(2) To ensure good thermal insulation and prevent heat from escaping along the length of the trousers, the inner edge of the trouser legs can be fitted with an elastic cuff.

Textile materials

The desire for outdoor activities and social contact, even in a cold environment, is very strong among wheelchair users. Therefore, when developing smart heating trousers, we must always choose textiles with good thermal insulation as well as water and wind-resistant textiles. Sweating and wetness on the skin, especially at the contact areas between the body and the wheelchair, require the selection of highly breathable and soft textiles to avoid skin irritation or inflammation. Paraplegics pull their trousers on their body and the trousers rub when sitting in a wheelchair, which requires the selection of a durable textile material for smart heating trousers.

Safety

Trousers heating areas

The permitted areas for heating in smart trousers are ankles, calves, knees and thighs. Heating of the buttocks, abdomen, crotch and areas of the hips and thighs that are in constant contact with the wheelchair is not permitted for health reasons for paraplegics.

Controlled regulation of the temperature of the microclimate in the trousers

(1) The maximum allowable temperature of the microclimate of the smart heating trousers must be

automatically controlled and regulated to ensure maximum safety from overheating of the body. In this study, the highest average skin surface temperature on the leg in a healthy person was found to be 31.7°C, measured in the thermally neutral zone and at rest. Research [26] shows that the optimal skin surface temperature at rest is 32.1°C – 34.3°C. If this temperature deviates between 1.5°C – 3.0°C, the person feels slightly cold or hot, and if it deviates by more than 4.5°C, they feel uncomfortable. Based on this data, the prototype of the smart heating trousers should be tested in the next phase of the research under different weather conditions and depending on the activity of the paraplegic.
(2) Based on the results of this study, the temperature of the microclimate inside the trousers should be measured on the inside of each trouser leg so that we have control over both legs and the possibility of regulating them, figure 3.
(3) The algorithm should automatically switch off the heating when the maximum allowable temperature of the trouser microclimate is reached so that the body does not overheat and the paraplegic is not injured.
(4–6) Based on this research, it is recommended that the heating of the trousers also be switched on and off via the application on the mobile phone.
(5) The application for regulating the temperature of the trouser microclimate should display both the real temperature of the environment and the temperature of the microclimate of both trouser legs on the phone.

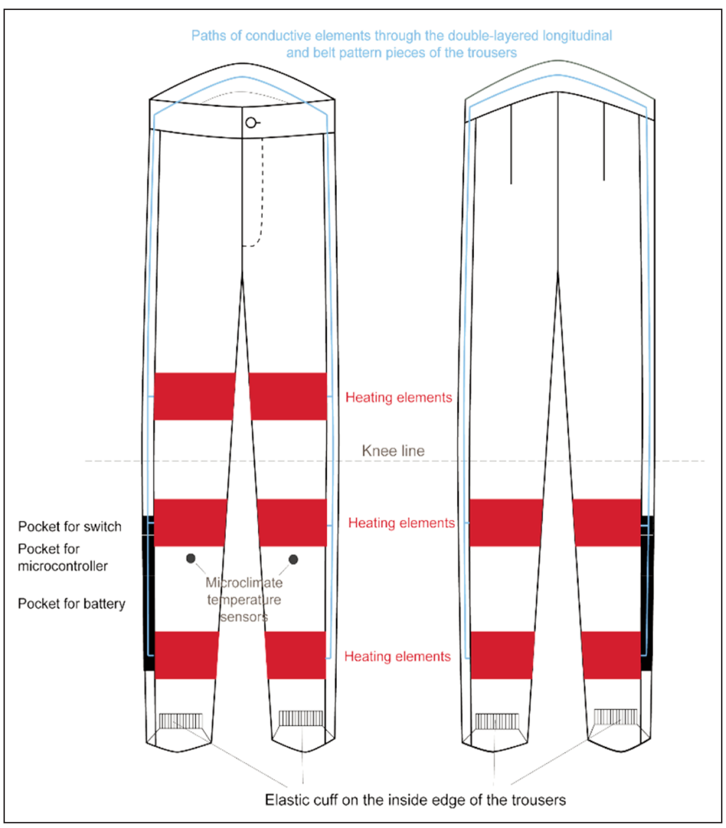


Fig. 3. A design of smart heating trousers

(6) The switch, the microcontroller and the battery should be located on the longitudinal side part of the trousers below the knee so that they do not come into contact with the wheelchair.

Special desires

Trousers appearance

(1–3) The smart heating trousers should have a classic pattern design, be made of functional textile material in neutral colours and look aesthetically pleasing.

Use

(1) Smart heating trousers shall allow wheelchair users to move outdoors for 1 to 5 hours (data needed to power the trousers with the battery).
(2) The battery must be removed from the trousers before washing, the microcontroller and switch are sealed inside the trousers to be waterproof.

CONCLUSIONS

The thermoregulatory centre of paraplegics is disturbed due to damage to the spinal cord, and the perception and regulation of lower limb temperature are impaired. The first part of this article deals with the design of a smart heating garment to protect the lower limbs of wheelchair users, while the developed prototype and the results of its tests are presented in Part 2 of this article.
Based on the findings from the survey of wheelchair users and measurements of skin surface temperatures of FMI and IMI, the design of smart heating trousers was developed to improve the thermal comfort of paraplegics. It covers the full range of parameters divided into four basic groups about the different problems, needs and desires of paraplegics. The proposed smart heating system in trousers informs the user of the ambient temperature and the temperature of the microclimate in each trouser leg and enables automatic temperature regulation, switching off when the required temperature is reached and providing heat for up to five hours.
The application potential is broader as the wheelchair user group also includes other groups of people with spinal cord injuries who have impaired thermoregulation of the lower extremities, as well as elderly people.

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Authors:

ANDREJA RUDOLF[1], VANJA KOLANOVIČ[2], MONIKA HUDOURNIK[3], JASNA ŠTAMPFER[4], JAKOB NOVAK[5], MATEJ BOROVEC[6], ROK BELŠAK[7]

[1]University of Maribor, Faculty of Mechanical Engineering, Institute of Engineering Materials and Design, 2000 Maribor, Slovenia

[2]University of Maribor, Faculty of Medicine, 2000 Maribor, Slovenia
e-mail: vanja.kolanovic@student.um.si

[3]3fs Nordic SI, d. o. o., 2000 Maribor, Slovenia
e-mail: hudournik.mony@gmail.com

[4]Žiher d.o.o., 2272 Gorišnica, Slovenia
e-mail: jasna.stampfer@gmail.com

[5]Inel d.o.o., 3000 Celje, Slovenia
e-mail: jakob.novak@inel.com

[6]AVL, Battery engineering, Hans-List-Platz 1, 8020 Graz, Austria
e-mail: matejbrvc105@gmail.com

[7]University of Maribor, Faculty of Mechanical Engineering, Mechanical Engineering Research Institute, 2000 Maribor, Slovenia
e-mail: rok.belsak@um.si

Corresponding author:

ANDREJA RUDOLF
e-mail: andreja.rudolf@um.si