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Thermal parameters measurement on fire fighter during intense fire exposition

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Abstract — **To improve rescuer safety, coordination and efficiency, the European program ProeTEX aims at developing new equipment for the intervention staff. This equipment is based on micro and nanotechnologies and consisted of smart textile integrated sensor to monitor physiological parameters, environment of the rescuer but also acquisition module and communication module.Thermal parameters are of primer interest. Internal temperature, external temperature and heat flux are relevant parameters to prevent heat stroke in fire fighter when exposed to intense fire. These parameters are recorded during fire exposition and highlight, on one hand, that the outer garment of fire fighters' equipment insulates the fire fighter from the external environment, and on the other hand, that the thermal monitoring is relevant.**

I. Introduction

This paper describes a part of the work carried out in ProeTEX, an European Integrated Project (Project FP6-2004-IST-4-026987) [1], which aims at developing new equipment for rescuers. These newly developed equipments integrate sensors to monitor physiological and environment, GPS, acquisition module, transmission module and batteries [2], [3]. The main goal of such smart textile is to improve safety of rescuer while they are saving life or protecting the environment. In the framework of ProeTEX, monitored parameters are ECG, respiratory rhythms, internal temperature, posture, external temperature, heat flux, etc. All these parameters are monitored either in the jacket or in the T-shirt. In this program, each parameter (measurement technics, sensors development, etc.) is under the responsibility of one partner. This paper deals with the monitoring of thermal parameters.

Electronic textiles (e-textiles) or smart textiles enable the development of personalized activity and healthcare monitoring capabilities by developing wearable interfaces [4], [5]. These multifunctional fabrics can integrate sensing, actuation, electronics and power functions [5], [6], [7]. The "Wearable Motherboard" [8], [9] developed by Georgia Tech. works as an interconnection structure to which commercial devices (sensors to monitor vital signs, such as heart rate, respiration rate, electrocardiogram, pulse oximetry and skin temperature for the recent versions [10], [11]) can be plugged. Another similar product is already available: SmartShirt, produced by Sensatex™. This system makes possible monitoring of some vital signs, such as heart rate, respiration and body temperature using the interwoven optical fibers as a motherboard for standard sensors connected by the optical fibers.

LifeShirt™ [12], produced by Vivometrics Inc. (Ventura, California) is a Lycra vest equipped with sensors. The core sensor system is based on inductive plethysmography measurement. The Lifeshirt™ device collects user parameters such as respiration rate, EGC, posure and physical activity, EEG skin temperature, etc. [13].

Considering the harsh environment meet by fire fighters, monitoring thermal parameters is of primer interest. The jacket composing the equipment is a thermal barrier in two ways [14]:

- from outside to inside, insulating the rescuer from the external environment ;
- from inside to outside, preventing the fire fighter to dissipate his/her metabolic heat.

Metabolic heat losses are significantly reduced as the activity level can induce high rate of metabolic heat production [15]. This situation can lead fire fighter to critical situation and more precisely to heat stroke. To minimize this danger, monitoring of thermal parameters is provided. Recorded parameters are internal temperature, environment temperature and heat flux. The work described in this paper presents sensors' location in the garments, recorded parameters and first preliminary tests.

II. Materiel and Methods

A. Measured parameters

With the mind to avoid heat stroke, thermal parameters are monitored on firefighters.

The most important parameter is internal temperature. When the core temperature increases of 1.5°C in relation to the temperature of the beginning of the intervention, the firefighter is ordered to come back.

Skin temperature is also monitored. This parameter gives information on the vasodilation/vasoconstriction state of the subject.

Heat flux provides information on the heat exchanges between the subject and its environment. Heat flux is monitored by using heat flux sensors composed of thermocouple matrixes.

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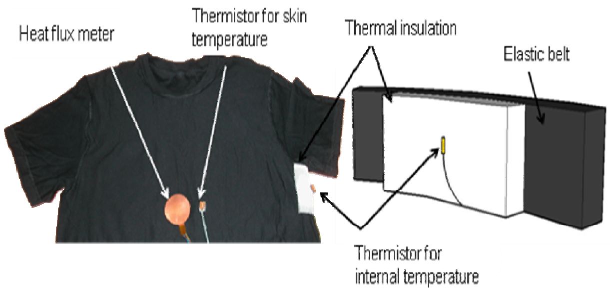

Figure 1: Sensors location in the T-shirt. Skin heat flux and skin temperature are monitored in chest location while core temperature is measured in axilla position. The right scheme shows the elastic belt over the sensors to ensure contact.

They supply a voltage proportional to the heat flow which passes through its surface.So measuring a heat flux is equivalent to measuring a voltage across the terminal of the heat flux sensor. The response is linear and the linearity coefficient is supplied by the manufacturer in µV/(W/m2). When heat flux is positive, heat goes out of the body. That is the usual case.

The subject removes the metabolic heat over-production to avoid internal temperature increase. When heat flux is negative, heat enters in the body. The subject gets heat from the environment and his/her core temperature increases.

B. Sensors location

Sensors used for the monitoring of thermal parameters are heat flux sensors (manufactured by CAPTEC ENTERPRISE® [16]) for the measurement of heat exchange and thermistor for the measurement of temperature (BetaTHERM®, 10 kΩ at 25°C, [17]). They are placed in the outer garment and in the T-shirt developed within the framework of ProeTEX.

Figure 2: Sensors location in the outer garment (yellow circle). The temperature sensor is located under the external layer. The heat flux sensor is placed in a pocket under the internal layer.

Figure 3: Firefighters posture during fire exposition

Two heat flux sensors are used to measure heat flux:

- The first one is placed in the jacket, in a pocket inside the outer garment in the chest area.
  With this sensor, heat flux through the jacket is measured.
- The second one is placed on the inner face of the T-shirt to be in contact with the skin. This sensor allows the measurement of heat exchange between the fire fighter and the under jacket environment.

Three thermistors are used:

- One thermistor is placed in the jacket, under the external layer to measure the external temperature.
- One thermistor is integrated in the T-shirt to measure the skin temperature
- The internal temperature is monitored with an insulated thermistor placed in axillary position. This measurement provides an acceptable temperature compare to rectal/oral temperature measurements [18].

Sensors placed in the jacket permit to evaluate the heat which goes through the jacket.

To ensure a good contact between the skin and the T-shirt, an elastic band is placed over the T-shirt.

Signal acquisition is performed with an OM-DAQPRO-5300 OMEGA® data logger [19].

C. Fire simulation

Preliminary test on this prototype was carried out at the training center of the Paris Fire Brigade (Brigade des Sapeurs-Pompiers de Paris). During these field trials, an urban fire was simulated in a container, to obtain intense fire and to reconstruct harsh condition met by fireman. A firefighter, 30 years old man, was static in front of the fire and thermal parameters were recorded. Two postures were adopted: on knees, chest vertically and on knees, curled up (figure 3). The fire exposition lasted 9 minutes.

III. RESULTS – DISCUSSION

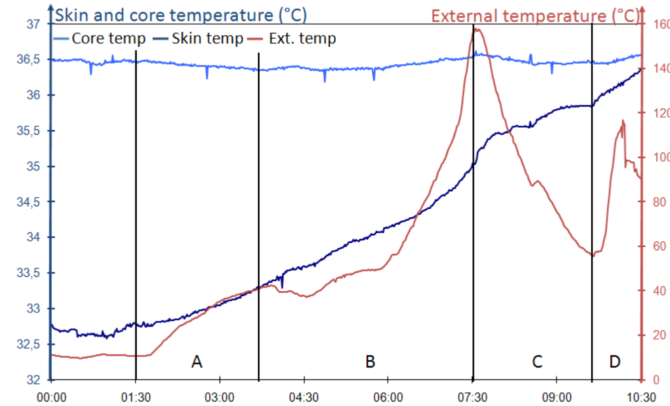

Figure 4: Skin, core and external temperatures during the fire exposition.

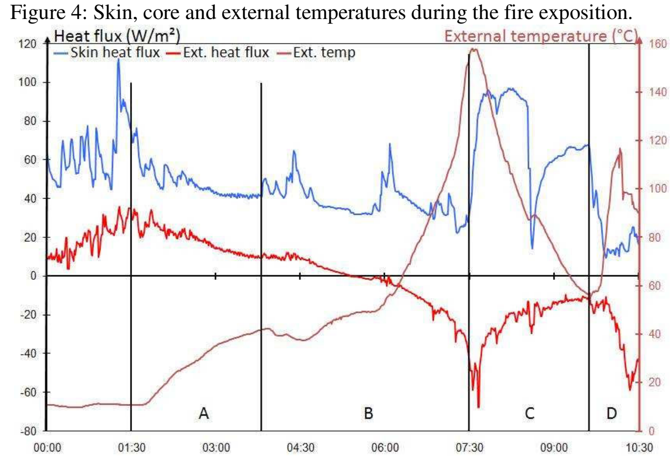

Figure 5: Heat flux and external temperature during the fire exposition

Figure 4 and
Figure 5 show the results of the fire exposition on recorded parameters.

- Phase A: the firefighter is on knees, chest vertically.

The external temperature increases of 12°C/min because of the fire. This reflects the important heat strain induces by the fire intensity.

Heat strain is also confirmed by the 2 heat fluxes decrease. The jacket heat flow decreases of about 8 $W/m^2/min$. Heat losses through the jacket are reduced. The temperature under the outer garment increase and the skin heat flow decreases of 3 $W/m^2/min$ to reach a value of 45 W/m^2. The fireman cannot remove all the heat produced by his metabolism.

The skin temperature increases of 0.5°C about 1.5 minutes. Thermoregulation mechanism starts. The firefighter is in vasodilation state.

The core temperature remains stable at 36.4°C.

During this phase the fireman is not in a dangerous situation from a thermal point of view.

- Phase B: the firefighter is on knees, curled up.

After the firefighter repositioning and a slight decrease, the external temperature increases with 2 different slopes: 10°C between the 4^{th} and 5^{th} minutes and a slope of 74°C/min after.

The outer garment heat flux decreases more rapidly than in phase A, with a slope of 16W/m²/min and becomes negative to reach -60W/m². Heat passes through the 3 layers of the jacket at time 3 minutes 45 seconds and warms the air layer under the jacket. Skin heat flux continues to decrease with a 10W/m² slope from 45 W/m² to 25 W/m². This reflects the higher heat strain and the lower possibility for the firefighter to remove his metabolic heat production.

The thermoregulation mechanisms become more important as shown by the skin temperature increase of about 0.8°C per minute to reach 35.5°C. The fireman has to remove his metabolic heat but due to the heat strain he cannot remove all this heat

The core temperature increases with a slight slope: 0.1°C in 3minutes 20 seconds.

This situation becomes dangerous. The temperature under the outer garment increases and heat passes through the jacket. The internal temperature increases.

- Phase C: water was sprayed on the fire to reduce temperature.

The external temperature decreases. The fire intensity is reduced.

This is confirmed by the increase of heat flux. The jacket heat flux increases of about 50W/m² in 2 minutes but remains negatives. There is less heat than previously which passes through the outer garment but the air layer under the jacket continues to be warmed.

Skin heat flux increases. Heat losses from the skin increase. The firefighter can remove heat.

This is reflected by the skin temperature increase with a lower slope (compared with phase B) of 0.3°C in 1 min and marks a stage at 35.8°C.

The core temperature decreases a little (0.1°C) during this phase.

When fire is spayed, the fire intensity is reduced and so less heat passes through the jacket. Heat losses increase. The situation is again dangerous because of the heat which passes through the jacket.

- Phase D: the firefighter is on knees, curled up.

The fire starts again. External temperature increases of 60°C in 30 seconds. The under clothing air layer is warmed by the heat which passes through the jacket.

The 2 heat fluxes decrease rapidly. The jacket heat flow decrease of 40 W/m² in 30 seconds and it is as low as during phase B.

The skin heat flow decreases to about 60 W/m². Heat losses are highly reduced: heat strain is more important.

The skin temperature continues to increase with a more important slope than previously.

The core temperature increases from 36.4°C to 36.5°C.

This new exposition to fire put the fireman in a dangerous thermal situation. The fire is highly intense. Heat strain is important as shown by all recorded parameters.

IV. CONCLUSION – PERSPECTIVES

In this study, the internal temperature sensor provides correct values of the core temperature (usually measured with oral/rectal sensors). This measurement is not influenced by the skin temperature variation as shown the continuous increase of skin temperature during the experimentation and the slight variation of internal temperature. The external temperature sensor give good information on the fire intensity and the heat flux sensors provide useful information on the heat exchanges.

The environment firefighters intervene is thermally straining. The experimentation describe bellow shows the relevance of thermal measurements in such cases. They allow an early detection of thermally risked situation. An internal temperature increase or a too long exposition to high entering heat flux (negative values of heat flux) could be detected with efficiency.

These field trials show the improvement to bring to the external temperature sensor and jacket heat flux sensor location. The most exposed area during fire intervention in the shoulders. The sensors will be replaced in the area.

Coupled with an adequate processing, continuous monitoring of thermal parameters would allow invoice of alarm to the manager who can order to the firefighter to come back in case of thermal danger. To develop this alarm, it is necessary to realize a measurement campaign in order to collect thermal data and to set threshold. The system probably needs a "learning" of the firefighter behavior because each subject reacts differently to thermal strain (adaptation to hot environment depends on the subject). The alarms would take into account all the monitored parameters to evaluate the danger situation of the firefighter.

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REFERENCES

[1] ProeTEX information available online: http://www.proetex.org/
[2] Curone D., Dudnik G., Loriga G., Luprano J., Magenes G., Paradiso R., Tognetti A., Bonfoglio A., Smart Garments for Safety Improvement of Emergency/Disaster Operators;
[3] Bonfiglio A., Nicola Carbonaro N., Chuzel C., Curone D., Dudnik G., Fabio Germagnoli, Hatherall D., Koller JM., Lanier T., Loriga G., Luprano J., Magenes G., Paradiso R., Tognetti A., Voirin G., and Waite R., Managing Catastrophic Events by Wearable Mobile Systems, Springer Berlin / Heidelberg, 2007, 4458, 95-105.
[4] M. Billinghurst, T. Starner, "Wearable devices: new ways to manage information", IEEE Computer, 1999, vol. 32 (1), 57-64.
[5] D. De Rossi, A. Della Santa, A. Mazzoldi, "Dressware: wearable hardware", Materials Science and Engineering C, 1999, vol. 7, 31-35.
[6] R. F. Service, "Electronic textiles charge ahead", Science, 2003, vol. 301, pp. 909-911.
[7] D. De Rossi, F. Carpi, F. Lorussi, A. Mazzoldi, R. Paradiso, E. P. Scilingo, A. Tognetti, "Electroactive fabrics and wearable biomonitoring devices", AUTEX Research Journal, 2003, vol. 3 (4), pp. 180-185.
[8] Georgia Tech Wearable Motherboard. Information available online: http://www.gtwm.gatech.edu/.
[9] C. Gopalsamy, S. Park, R. Rajamanickam, and S. Jayaraman, "The wearable motherboard\™: The first generation of adaptive and responsive textile structures (ARTS) for medical applications" , 1999, J. Virtual Reality, vol. 4, pp. 152-168.
[10] S. Park and S. Jayaraman, "Enhancing the quality of life through wearable technology", IEEE Engineering in Medicine and Biology Magazine, 2003, vol. 22 (3), pp. 41-48.
[11] S. Park, C. Gopalsamy, R. Rajamanickam, and S. Jayaraman, "The wearable motherboard: an information infrastructure or sensate liner for medical applications," Stud. Health Technol. Informatics, 1999, vol. 62, pp. 252-258.
[12] Vivometrics Inc., LifeShirtTM, information available online: http://www.vivometrics.com/site/index.html.
[13] Paul Grossman, "The Lifeshirt: A Multi-Function Ambulatory System That Monitors Health, Disease, and Medical Intervention in the Real World", Proc. of International Workshop: New Generation of Wearable Systems for e-Health: Towards a Revolution of Citizens' Health and Life Style Management?, 2003, Lucca, Italy, pp. 73-80.
[14] Havenith G., Heat balance when wearing protective clothing, Ann. Occup. Hyg., 1999, Vol 43, N° 5, 289-296
[15] Dittmar A., Delhomme G., Schwenzfier L., The human body: a complex thermal controlled system, Thermal protection of man under hot hazardeous conditions, procedings, 1999, 1-20
[16] CAPTEC Enterprise® information available online: http://www.captec.fr/
[17] Betatherm® thermistor information available online: http://www.betatherm.com/datasheets/db/pdf/1129810305.pdf
[18] Lodha R., Mukerji N., Sinha N., Pandey R.M. and Jain Y., Is Axillary Temperature an Appropriate Surrogate for Core Temperature?, Indian Journal of Pediatrics, 2000; 67 (8) : 571
[19] OMEGA® OM-DAQPRO-5300 information available online: http://www.omega.com/pptst/OM-DAQPRO-5300.html