Conceptual design of a sensory shirt for fire-fighters (accepted version)

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Abstract

A large number of fatal accidents of fire-fighters during operations can be attributed to circulatory collapses due to cardiovascular diseases or heat stress. A recent project thus aimed at developing a highly functional, reliable and suitable system which can be used under different conditions such as common in-door operations. Measurement of vital signs, like ECG, breathing, and skin temperature, had to be combined with limited weight, acceptable skin comfort, affordable price, and fast and easy dressing and connecting to the electronics in the fire-fighter jacket. The article gives an overview of technical and clothing technology aspects of the developed sensory shirt.

Keywords

Sensory shirt, fire-fighters, ECG, skin temperature, breathing sensor, pattern construction, conductive paths

When a fire-fighter has to enter a burning building, direct contact with the fire is not the only possible cause of a fatal injury. Instead, the U.S. Fire Administration reports that during the last ten years about 50 % of fatalities occurred due to stress or overexertion, for the year 2010 even more than 60 % [1]. This category includes fire-fighter deaths of cardiac or cerebrovascular nature, such as heart attacks (the most often cause), strokes, or other events like extreme heat stress. The high ratio of this fatality cause can be attributed to the extremely strenuous physical work during fire-fighting.

Our project attempts to decrease the number of fatal injuries of fire-fighters by constant monitoring of their vital signs. Other recent projects dealing with similar approaches show the problems arising in the construction of such a sensory shirt: Firstly, especially the ECG electrodes, but also the breathing sensor can be disturbed by unintentional movements of the shirt relative to the body of the fire-fighter. Even when a chest strap is used, like in sports, such unintentional displacements cannot always be avoided. Especially for the ECG electrodes, good positions for constant signal detection without interruptions can hardly be found [2]. This finding is of particular importance for a sensory shirt for fire-fighters, since the extreme movements during fire-fighting have to be taken into account, and on the other hand the fire-fighters must not be constricted by a very close-fitting chest strap. However, in scientific literature, no articles can be found about the special demands of intelligent textiles on pattern making. For our project, pattern making has to find a compromise between reliability of the vital sign measurements and the fire-fighters' comfort. Additionally, the design of the shirt has to guarantee that fire-fighters will not resist wearing the shirt due to its optical appearance.

Secondly, textile data lines have to be integrated into the shirt since usual cables could cause some disturbance in the tight-fitting underwear. The integration of such conductive yarns has been examined in several recent projects. Conductive yarns have, e.g., been integrated into textiles by weaving, sewing or embroidering [3,4] as well as in shoes [5]. The connection of common non-textile sensors by conductive textile panels [6] or by different conductive yarns [7] has also been examined. In all these projects, however, only non-elastic textiles have been used as base for the conductive paths, while in a sensory shirt, a highly elastic material is used. Even conductive yarns which are claimed to be elastic (e.g. by Ohmatex [8] or Zimmermann [9]) can be elongated by only a few percent, thus they cannot be integrated linearly into the sensory shirt. In the EU project STELLA, solutions for conductive prints and for elastic films with integrated conductive wires have been developed [10]; however, a procedure to integrate conductive yarns in elastic textiles has not been examined.

And finally, the connection between the textile data lines in the shirt and the electronics which analyze and transmit the data in the fire-fighter jacket must allow for fast and reliable handling. This connection has to be closed during dressing for fire-fighting operations. Thus, the connector has to be closed within seconds, must not open unintentionally during the operation, and must direct the fire-fighter to the correct position (like a rotatable connector) without the possibility to connect both sides in a wrong direction.

In other recent projects dealing with monitoring vital signs of fire-fighters, these problems did not occur as common non-textile electrodes were used [11-16] and the electrodes were often not even integrated into a sensory shirt to guarantee correct positioning. Such approaches are not ideally suited for the demands in the hard workday of a fire-fighter.

Our paper gives an overview about the conceptual design of a sensory shirt for fire-fighters, including positions of textile ECG electrodes and textile data lines; a new pattern making concept to support the acceptability of the shirt for fire-fighters, and a possibility to create a fast, easy and reliable connection between the sensory shirt and the electronics in the fire-fighters' jacket.

Pattern making of the shirt

The main task of the shirt is to position the ECG electrodes as well as breathing and temperature sensors and to guarantee a sufficient pressure of the ECG electrodes on the skin. Thus, we firstly investigated the reliability of the skin contact for possible electrode positions. Different probands were dressed with a tight-fitting shirt and pants and had to perform several movements, like running, rotating the upper part of the body, pulling a water hose, using an axe, etc. The contact between shirt and skin was detected. The results are exemplarily shown in Fig. 1 for the case of a running person: While several areas of the body (marked white) are still in contact with the shirt or the pants, respectively, other areas loose the contact to the garment (marked black). In the shaded parts, the behaviour differs, depending on the test person.

Additionally, it has to be taken into account that the electrodes should not be placed directly on muscles, since the electric muscle activity strongly disturbs the ECG signal. This means that the arms and legs, although the contact is never lost here, should not be used to place the electrodes since fire-fighters are always in motion during fire-fighting operations.

Due to the results of this test, the electrodes are used only in the single other area where the skin contact was never broken, i.e. below the breast, especially on both sides of the body.

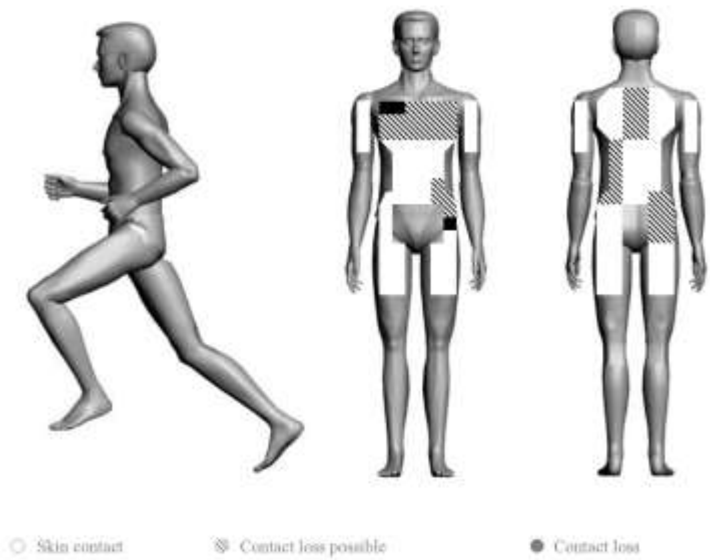

Fig. 1. Example of skin contact test results for several probands, using tight-fitting clothes.

The next step was to examine the ideal pressure of the electrodes on the human body – if the pressure is too low, the signal gets noisy; if the pressure is too high, the comfort during wearing the shirt will decrease.

On the one hand, a questionnaire was developed to interview several students and scientists of the Faculty of Textile and Clothing Technology of Niederrhein University of Applied Sciences as well as fire-fighters who wore first prototypes of the shirt and checked different relative elongations of an elastic band which was inserted below the breast, surrounding the proband’s body.

Since measuring the force was only possible for a small group of probands, the questionnaire was related to the relative elongation which could easily be defined by the people participating in the test themselves. Although relative elongation and pressure on the skin are not absolutely related (Fig. 2), measuring the relative elongation had the advantage to be measured much more easily and thus by more probands. The questionnaire resulted in the finding that for the elastic band used here, a relative elongation of 20 % lead to the maximally accepted pressure on the skin.

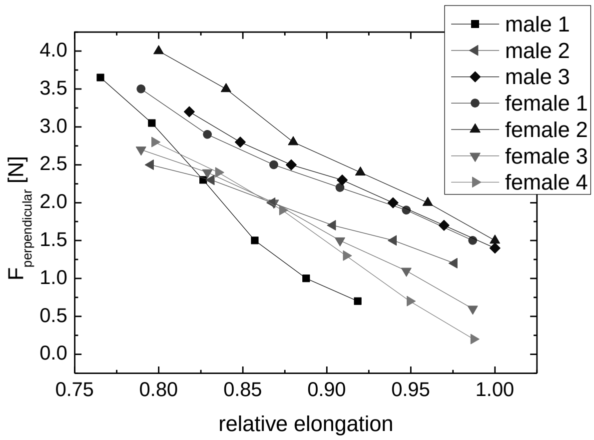

Fig. 2. Comparison between relative elongation of the elastic band and the force F, measured on the sides of the body.

To find the optimal balance between electrode performance and wearing comfort, ECG signals have been detected for different relative elongations between 5 % and 20 %, in different situations, such as standing, walking, running, rotating the upper body etc.
While for a person sitting or standing without movement, a relative elongation of the elastic belt of 2-5 % is sufficient to result in nearly perfect signals (rating 4-5), even small movements lead to a strong decrease in the signal quality. For ECG measurements during a rotation of the upper body or during running, a significantly higher relative elongation of 20-25 % is necessary to maintain good measurements (Fig. 3). This finding results in an ideal relative elongation of ~ 20 % as optimal compromise between wearing comfort and signal quality.

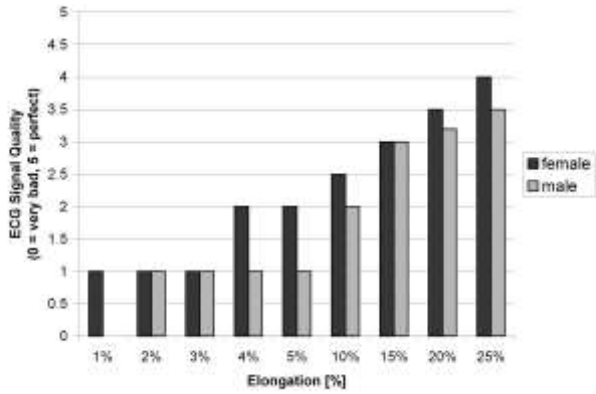

Fig. 3. ECG signal quality (from 0 = very bad to 5 = perfect) for different relative elongations of the elastic belt, measured by female and male probands during rotations of the upper body. The last value (25 % elongation) is outside the comfort range which ends approx. at 20 % elongation. The signal quality rating was defined as follows: 0 = no signal, 1 = only QRS complex visible, i.e. pulse measurable, but disturbance larger than signal, 2 = only QRS complex visible, i.e. pulse measurable, with disturbance smaller than signal, 3 = only QRS complex and T wave visible, 4 = QRS complex, T wave and P wave visible, but still noise disturbing the signal, 5 = QRS complex, T wave and P wave visible and nearly no noise.

Additionally, the appearance had to be taken into account. Since most male probands did not want to wear a shirt with a visible elastic belt below the breast, we decided to construct a double shirt with an inner and an outer layer (Fig. 4). The inner part contains the technical elements, i.e. the ECG electrodes, the temperature sensor (white “T” in the neck), and the breathing sensor (inside the elastic belt, as well as the ECG electrodes). The connections of these sensors with the bonding point in the neckline front (white marks in the left panel) are also integrated in the inner shirt, while the outer shirt is only used to conceal the elastic belt and the functional elements.

Fig. 4. Sensory shirt with inner and outer part (left panel); proband wearing a prototype of the sensory shirt where the functionality is only visualized by the ECG symbol (left and right panel).

Integration of conductive yarns

In sewing, wearing and washing trials, a conductive stainless steel filament yarn sewn in an undulating form turned out to be ideally suited as conductive thread. Opposite to extruded yarns or braids and to coated wires, these conductive yarns can almost not be felt through the shirt; they are extremely tear-resistant; they are not influenced during the desired 50 washing cycles by oxidation or by mechanical impacts, and they are nevertheless not rigid enough to significantly influence the textile material on which they are sewn.

A complex sewing instruction has been developed to allow for the optimal embedding of the conductive yarn integration into the sewing process.

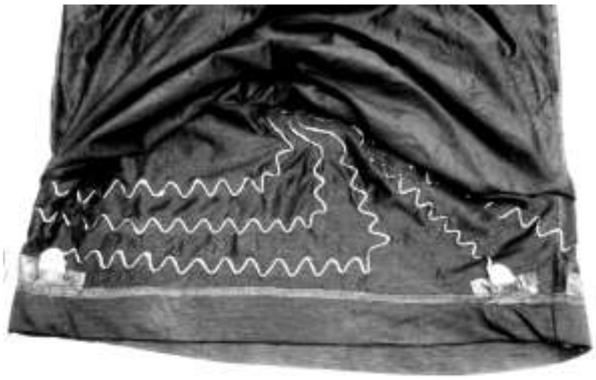

Fig. 5. Inner shirt with stainless steel filament yarns sewn on the shirt in an undulating form, contacting the ECG electrodes and the other sensors.

Electric connections between shirt and jacket

While in the shirt, all electric connections are produced in a textile way – i.e. by sewing –, the jacket contains common electrical elements and connections which are normally soldered. The electric connection between shirt and jacket thus has to connect the textile and the “hard-electronic” part. Additionally, not only one or two connection lines are necessary, but approx. 7 or more contacts (in the recent version of the shirt, there are 3 ECG contacts, 2 temperature sensor contacts, and 2 breathing sensor contacts). Thus, a connection via a conductive hook and loop fastener cannot be used, since it would have to be too large to avoid erroneous contacts. Additionally, a direct contact between sensory shirt and jacket is not always given, since normally a pullover or a T-shirt is worn which separates both layers. Thus, a flexible connection with an additional connection strip has been chosen. The connection strip starts at the front neckline, containing all textile conductors, and has a connector at its end. The opposite part of the connector is integrated in the left collar of the jacket.

Several common connectors have been tested taking into account washability and handling. All flat connector versions under examination have been found to be either too heavy, too small (and thus too hard to handle), too sharp-edged, not safe from erroneous unplugging or unsuitable due to other reasons. Especially the requirement that the fire-fighters have to be able to close the connection “blind” (because the plug inside the collar would only be visible in a mirror) has been found to prevent the use of flat connectors.

Thus, round connectors in different forms (plastic / metal, with / without safety ring, different numbers of contact pins) have been examined. These connectors can be closed more easily by rotating both parts against each other. In washing trials, plastic connectors without additional waterproof finishing have shown to be best suited, since they are washable for at least 50 cycles and on the other hand more light-weight than the waterproof connectors, which is an important factor for the acceptance of the shirt. Additionally, they are much less expensive than metal ones.

Conclusion

In a recent project, a sensory shirt for fire-fighters has been developed. Besides the development of novel textile ECG electrodes which can also be used for people in movement, several technical aspects concerning the pattern construction and the integration of sensors and conductive paths into the shirt had to be taken into account. New approaches led to solutions with the necessary technical functionalities and the demanded acceptance of the shirt by the fire-fighters.

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