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Design of smart garments for sports and rehabilitation

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Abstract. Physical exercise has proved benefits for general health [1] and can reduce the number of sports injuries to one third [2]. However, an athlete that has been injured during sports practice may omit this out of fear of discrimination, and worsen the injury in the weight room, during strength training [5]. Monitoring physiological status of an athlete or rehabilitation patients during training may thus help the person to get an earlier intervention, preventing injuries from getting worse. With this in mind, we propose a set of compression garments – shirt and leggings – with textile sensors to continually monitor heart and muscle activity, breathing rate and temperature. This paper reports the design of the garments and production of the shirt, which comprised a 3-lead ECG system, sEMG (Surface Electromiography) electrodes and a breathing sensor. The ECG (Electrocardiography) system was tested and presented some good results, in particular for very even movements, but the system still needs to be improved, in order to get a better signal, when it comes to movements with a considerable amplitude.

1. Introduction

Studies have shown that physical activity has positive effects in the prevention and treatment of several diseases, such as cardiovascular disease, diabetes, cancer, hypertension, obesity, osteoporosis, and depression [1], and it can contribute to prevent sports injuries, reducing the incidence of sports injuries to one third [2]. Strength training exercises, for instance, is a common practice between athletes, to improve muscle strength and power [3] and is commonly prescribed for health and fitness, athletic training, and prevention or rehabilitation of muscle and bone injuries [4].

One of the issues related with athletes' injuries is early detection. An injury may only be spotted in the weight room, but it may not have occured there. This can happen because an athlete may get injured in the field, and not tell anyone, fearing prejudice, and the injury only worsens in the weight room [5].

In order to increase the quality of training for athletes, rehabilitation patients or other pratictioners, preventing injuries and other health issues, or to avoid them to get worse, it is important to monitor the person while exercising. A system that provides EMG data in real time may help detecting injuries before they get worse, allowing early intervention, or evaluating the quality of exercise of a patient during rehabilitation.

Previously [6], a prototype of a seamless long sleeve t-shirt for cardiac and muscle activity monitoring was reported. The shirt had 4 ECG electrodes and two sEMG (surface electromyography) electrodes located on the biceps. The ECG system performed well, but moving the arms had a negative impact on the signal's response, since two of the electrodes were too close to the armpit. The sEMG electrodes didn't provide any signal.

Lage et al. [7] have presented a prototype of a sleeveless knitted shirt with knitted electrodes to monitor heart rate, as well as a knitted moisture sensor. The shirt was produced in a seamless knitting machine and the sensors are knitted with a silver coated polyamide yarn. For the heart rate measuring, two electrodes are located bellow the chest. The authors found that when the subject is quiet, the system captures a good ECG signal, but when he starts to move the arms, the signal presents motions artifacts and some heart beats are missed.

Manero et al. [8] designed running leggings for muscle activity monitoring, during training. The garment has three pairs of embroidered electrodes to detect EMG signals from the quadriceps, namely the *Vastus Medialis*, *Vastus Lateralis* and *Rectus Femoris*. The system seems to be reliable, according to the performance tests, being able to determine muscle fatigue.

Some products have even made its appearance in the market and the interest for smart clothing has been rising. Athos® has a set of compression garments (shirt and shorts) that has printed sensors with conductive rubber to give information about heart rate, breathing rate and muscle activity [9]. Myontec developed cycling shorts that use textile electrodes to monitor muscle activity of the quadriceps and hamstring muscles [10]. Hexoskin uses a combination of textile and conventional sensors in a shirt to provide information about heart rate and variability, breathing rate, oximetry and activity parameters [11].

Incorporating textile electrodes (or other sensors) presents several challenges in terms of signal reliability. In order to improve the performance of the textile electrodes used in ECG and sEMG, some authors suggest that the electrodes should be covered by a waterproof membrane [12]; should be stretched, but stabilized at the same time [13]; and the structure of the textile substrate should be dense [14] and smooth [15]. Compression has also shown positive results in the quality of the acquired signal [6], since it presses the electrodes against the skin, improving the contact, and holds the electrodes in a steady position.

In this paper, the design and development of a set of sportswear garments – long-sleeve t-shirt and leggings – that integrates textiles sensors for real-time monitoring of the person's activity and physiological data is proposed.

2. Materials and Methods

A set of compression shirt and shorts was designed. The set incorporates ECG, sEMG, breathing and temperature sensors, to continually evaluate the athlete or patient's physiological data. The long sleeve knitted shirt has textile sensors to monitor heart and muscle activity, breathing rate, and skin temperature.

To select the muscles, the work of Delavier [16] was used as a reference. The author describes all strength exercises usually performed in the gym and highlights the muscles that are being worked in each one. By analyzing his work, we conclude that the muscles that are more subjected to effort are the *deltoids*, *pectorals*, *biceps brachii*, *trapezius* and the *triceps* (for the arms), as well as the *quadriceps* (all its portions), *biceps femoris* and *gastrocnemius* (for the legs). The *brachioradialis* muscles was also included, because it is a large muscle of the arm.

The shirt also includes a 3-lead ECG (which can use 3 or 4 electrodes) that, aside from measuring heart beat and intermittent arrhythmias, is a cost-effective way of detecting atrial fibrillation, thus contributing to the prevention of stroke [17].

Breathing rate and temperature monitoring was also included, since they are important parameters to be measured during rehabilitation [18] and the possibility of measuring these vital signs with e-textiles has been reported.

Figure 1. Sketch of the garments

At this first stage, only the shirt was produced, in a seamless knitting machine, which produces the knitted fabric in the form of a tube that can have the size of the body, thus eliminating the need of side seams, and uses jacquard technology to knit patterns in the same substrate. The fabric produced is a polyamide/elastane pique knitted fabric. For the knitted conductive elements (electrodes and conductive tracks), a polyamide/silver yarn – Elitex 110/f34 – was used. The electrodes form a 3D structure (figure 2), reported in [19], while the tracks have the same structure as the rest of the garment. When a jacquard pattern is produced in this kind of machine, the conductive yarn is either cut or loose in the areas that are not being knitted, which means that two tracks can come in contact with each other, which is not desired. So, the undesired yarns need to be cut before insulating them. To insulate the tracks (inside and outside), TPU film was used – Bremis Exoflex. It also decreases the fabric's elasticity, thus creating some compression.

Figure 2. Knitted electrodes

To accurately position the embedded electrodes in the knitted fabric position and study the garment's patterns, a mock-up version of the garment was made and the positions were marked with the shirt dressed. This information was used to digitally design the pattern and produce it in the seamless machine. Figure 4 shows the garments patterns and jacquard pattern in the desired position.

Preliminary tests were executed using a *Shimmer3 ExG* device that can perform a 4-lead ECG (LA-RA, LL-RA, LL-LA and Vx-WCT) or measure EMG signals in two muscles, at the same time. At this stage, only the ECG tests were performed, with the subject standing still and performing *high-pulley curls*. We wanted an exercise that would imply the movement of the arms, to study the effect of these movements on the ECG signal. All tests were carried out with dry and wet electrodes, for comparison, and with and without pressure applied over the electrodes. To create additional pressure, a stretch band was used.

3. Results and Discussion

It figure 3, it is possible to observe the prototype of the knitted shirt. Figure 3a shows the outside of the shirt, where almost all conductive parts are protected by a black TPU layer, except for a small area in the chest, where conductive wires will be sewed to connect to an external device. In the inside of the shirt (figure 3b), only the electrodes are visible, as well a rectangle below the chest that represents the breathing sensor (it will not be considered in these experiments).

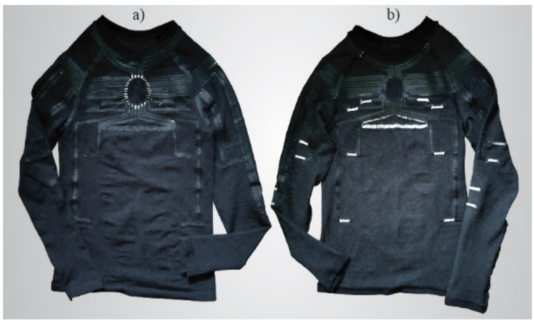

Figure 3. Shirt's prototype: a) exterior and b) interior

When dressing, one needs to manually position the electrodes over the desired muscle, which may require previous training. On the other hand, the TPU inside layer prevents the shirt from sliding, thus keeping the electrodes at the same place. That's especially true for the sleeves, because TPU covers a wider area, unlike the belly region, where only a small portion of this material was used to protect the ECG electrodes (LL and RL).

Figures 4 and 5 show the ECG signal obtained from lead LA-RA with the subject standing still. A full ECG wave is more or less visible in all tests, but there is more noise when the electrodes are dry (Figure 4), which was expected and follows the results from several studies made by other research teams. In both cases (dry and wet), pressure has a positive effect, since it decreases noise, thus showing a cleaner ECG wave.

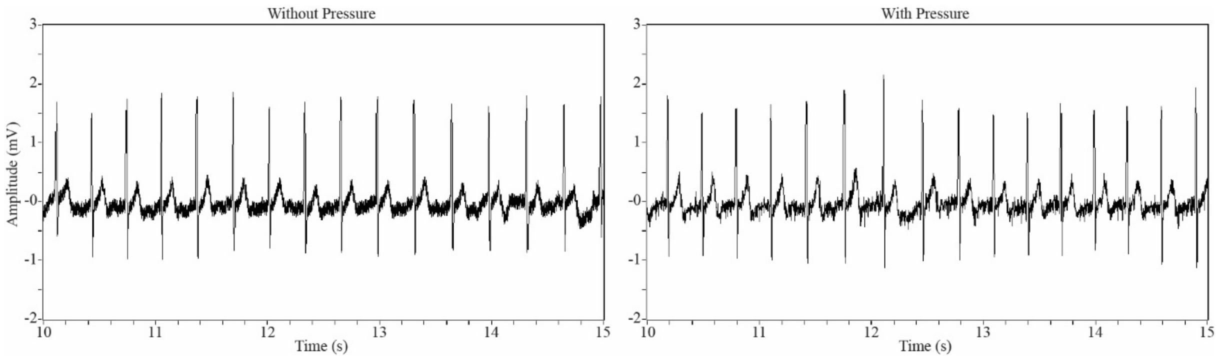

Figure 4. ECG signals in static position, with dry electrodes

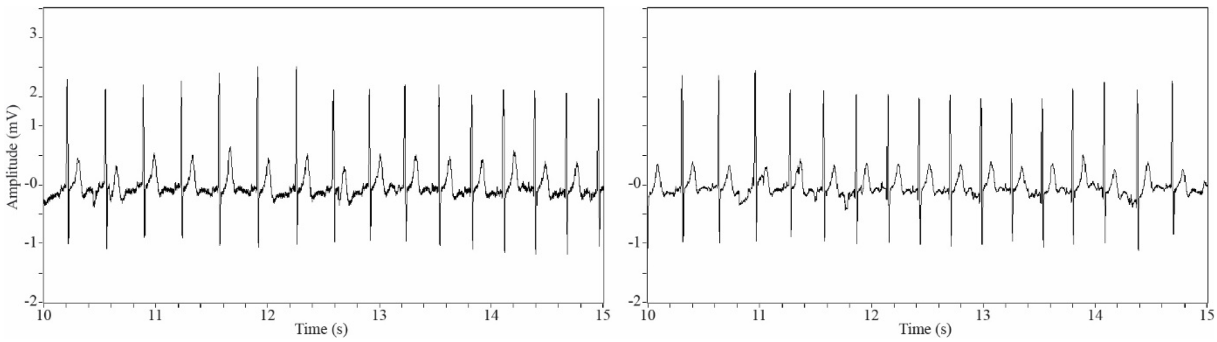

Figure 5. ECG signals in static position, with wet electrodes

When performing front presses, the results get worse (figures 6 and 7). When not wearing the stretch band, the whole range of exercise can be observed (arms moving down – arms down – arms moving up – arms up). When the arms are moving, some oscillations are visible and when the arms are up, there is considerable noise. That happens because when the arms lift, the shirt is stretched and the electrodes loose contact with the skin. The area around the armpit can thus be a tricky area to put textile electrodes.

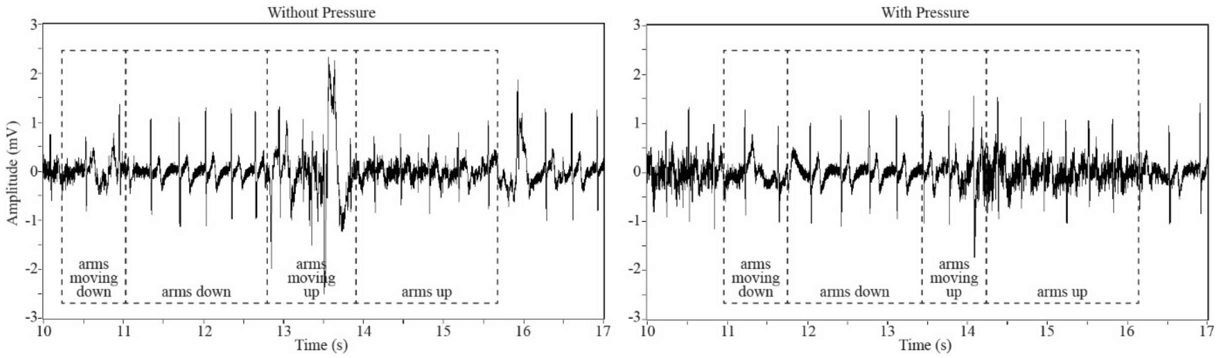

Figure 6. ECG signal while performing front presses, with dry electrodes

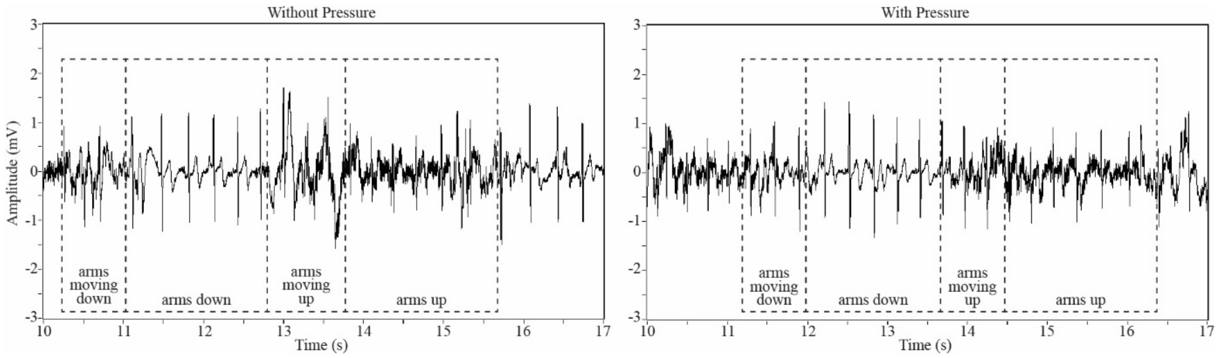

Figure 7. ECG signal while performing front presses, with wet electrodes

The measurement system used seems to be very susceptible to ambience noise. The tests had to be carried out a few meters from the laptop, otherwise noise would overlap the ECG signal.

4. Conclusion

In this paper, ECG measurement using the developed shirt is reported. In the future, tests will be carried out using the EMG electrodes. New experiments need to be prepared until a full clean ECG wave is obtained. This may include finding a more suitable spot to place the electrodes or finding a way to keep them in place, even when moving the arms, without compromising comfort. Alternatively, the movements of the arms can be studied in order to determine the best places to include electrodes.

The TPU film helps keeping the electrodes in place due to the compression created and the rubber like surface that keeps the fabric from sliding over the skin. These features can (and shall) be explored in future experiments.

To carry out the experiments, a *Shimmer3 ExG* device was used, but a device that follows the aesthetic and functional requirements of the garments shall be designed. This is an important objective if we want to shift from a laboratory setting to a user-friendly product that can be used by a person in real scenarios.

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