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A PRACTICAL APPROACH CONCERNING THE CAPACITIVE ACQUISITION OF THE ELECTROCARDIOGRAM IN A MOVING WHEELCHAIR

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Abstract: Capacitive sensing of the electrocardiogram allows inconspicuous monitoring of the most well-known electrophysiological signal. Wheelchair users with cardiac maladies would benefit from ECG unobtrusive monitoring. However, motion and daily life activities impose strong artifacts to the signal acquired. This study aims at the extended capacitive electrocardiogram acquisition with and without movement. To validate the hardware, and discern on its capability to do long-term monitoring, recordings of 5 minutes were made for immobile and moving wheelchair, and compared with the contact ECG obtained using a reference equipment. Seven subjects tested the immobility scenario, with tight agreement between contact and contactless ECG. Fourteen realistic combinations of inclination and speed were tested on a treadmill, with the capacitive ECG sensing hardware being able to provide comparable results to the reference equipment. Thus long-term capacitive ECG acquisition by means of the hardware setup developed was found feasible and reliable within the test maximum limits of 7 km/h and 4.4% of inclination.

Keywords: cardiac continuous monitoring, capacitive electrocardiogram, treadmill, unobtrusive instrumentation, wheelchairs.

1. INTRODUCTION

Several groups of wheelchair users need permanent monitoring of their cardiovascular condition, e.g. stroke victims in recovery, elders, or diabetics [1]. Given the limitations imposed by the normal electrocardiogram (ECG) acquisition relying on the placement of conductive electrodes over the body surface, a contactless solution with embedded and unnoticeable electrodes is preferable. Thus, embedding cardiac system sensing devices in wheelchairs is both necessary and attractive, for instance, as it allows monitoring the subject's state without constraining his daily life autonomy [2].

Embedded solutions based on the processing of the ballistocardiogram (BCG) or of the photoplethysmogram (PPG) have been presented [3–6]. However, the ECG is the most well-known physiological signal, and it provides detailed information on cardiac status [7]. Therefore, a capacitive coupled ECG acquisition system would be a most favourable solution.

Devices using electrodes with coupling to the subject through isolating media have been developed in the recent past, with the applications spanning from shirts to chairs, toilet seats, and bath tubs [8–11]. Besides the lack of studies in wheelchairs, in this scenario movement artefacts become a staggering concern. Thus, 5 minutes recordings were taken to infer the stability and robustness of the sensing solution regarding artefact generation.

A hardware setup implementing capacitive electrocardiography was developed. The electrodes were placed within a cover attached to a wheelchair's backrest, thus being imperceptible to the user. This unconstrained monitoring solution was assessed for eight healthy subjects in a motionless scenario during five minutes. Records of the same duration were taken in an exercise treadmill for seventeen different combinations of speed and inclination, from 1 to 7 km/h and inclinations from 0 to 4.4%. This set of tests was used to inspect the reliability of the capacitive ECG acquired from the developed hardware, for a realistic use by subjects with different anthropometric characteristics.

This paper presents a synthetic analysis of the results gathered. Its organization is as follows: section 2 describes the sensing device; section 3 discusses the results of the validation tests taken in the two scenarios; lastly the conclusions drawn appear in section 4.

2. WHEELCHAIR HARDWARE

The ECG sensor is shown, together with a two euro coin for scale perception, in Fig. 1. Its signal conditioning circuitry is displayed in Fig. 2 and was embedded in the wheelchair. This monitoring setup is totally unobtrusive, and the subject is unaware of the continuous monitoring.

Capacitive ECG sensing is based on the potential change at the probe conductive surface, reflecting the biopotential changes occurring at the body surface, propagated through the dielectric constituted by the intermediate textile. This causes the impedance between the skin and the electrodes to be extremely high, which makes crucial a careful design of the sensing probes. The addition to the seat of a large plane electrode connected either to the reference voltage or in a driven right leg scheme is also significant to reduce power line interference [12], [13].

The electrodes designed have a copper surface with an area of 33.75 cm^2, with the plane electrode having an area of 560 cm^2. Shielded coaxial cable and RF connectors are used to connect the signal to the conditioning circuitry. Proper impedance matching was achieved by using Texas Instruments INA116 operational amplifier (bias current 3 fA, input impedance $>10^{15}$ $\Omega \parallel 0.2$ pF, and common mode rejection ratio of 84 dB).

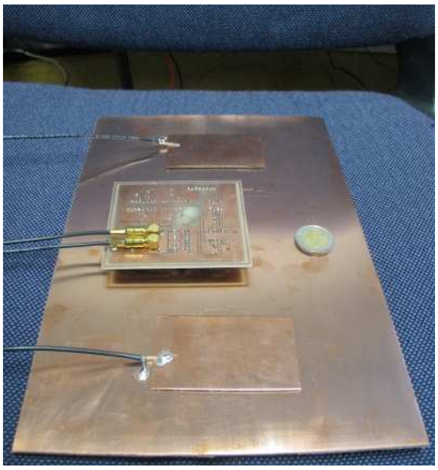

Fig. 1. Two leads, driven ground plane sensor and the PCB with the capacitive electrocardiogram signal conditioning circuit. Note the size of the hardware when compared with the two euro coin.

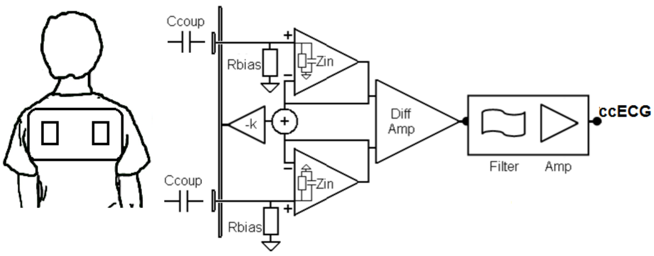

Fig. 2. Diagram of the capacitive ECG sensing setup with the respective signal conditioning circuitry. The intended position over the person's back is also shown.

To provide a reference to the system, a Medlab P-OX100 system was used. This device provides three analogue outputs: the electrocardiogram (ECG) waveform, the instantaneous heart rate, and the oxygen saturation of the subject. These outputs are enabled by the addition of three leads gripped to the volunteers' limbs for the ECG and a finger PPG sensor.

The capacitive ECG and the three reference signals are synchronously recorded, so that reference data, namely an ECG waveform, is available. These four voltages are digitalized and sent via WiFi to a laptop by means of a 16 bit data acquisition board (National Instruments 9205) programmed to sample the analogue inputs at 1 KHz and plugged to a compatible wireless module (NI WLS-9163).

3. RESULTS AND DISCUSSION

A total of 8 volunteers tested the system. Their age was 23.0 ± 8.9 years old (average ± standard deviation), the weight was 75.5 ± 11.3 kg, and their height 1.79 ± 0.07 m. The body to mass index averaged was 23.5, with three subjects in the overweight (25-30) region and five in the normal (20-25) region.

3.1 Static wheelchair

The subjects were seated on the wheelchair and the finger PPG and a 3 limb-lead ECG of Medlab P-OX100 were connected. During 5 minutes, the wheelchair did not move, and the subjects were told to be still, while allowed to talk normally.

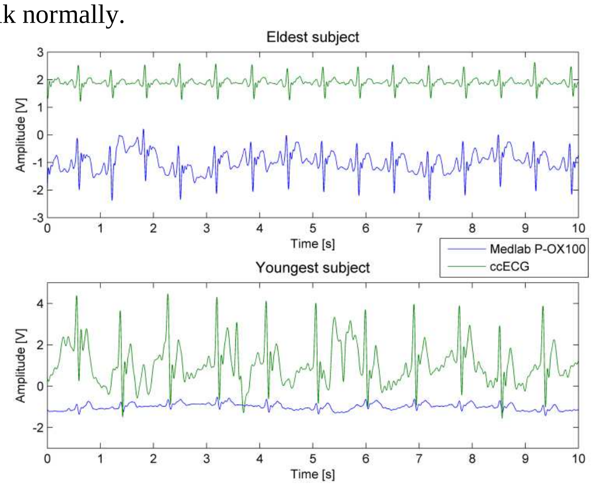

Fig. 3. ECG signals acquired from the eldest and the youngest subjects with the wheelchair stopped. Graphs show ECG from Medlab P-OX100 (blue, lower position within graph) and capacitive ECG (green, upper position). To improve readability the signals were shifted upwards and downwards, but their amplitudes weren't changed.

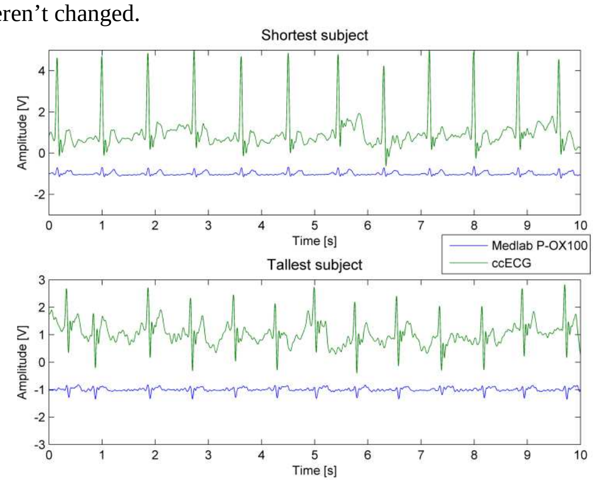

Fig. 4. ECG signals acquired from the shortest and the tallest subject (20 cm variation) with the wheelchair stopped. Graphs show ECG from Medlab P-OX100 (blue, lower position within graph) and capacitive ECG (green, upper position). To improve readability the signals were shifted upwards and downwards, but their amplitudes weren't changed.

In this immobility scenario, the capacitive ECG (ccECG) sensor worked properly, and the best signal possible was obtained. The eldest and the youngest subject have a portion of their signals presented in Fig. 3. The same happens in Fig. 4 for the shortest and tallest subjects.

Analyzing the example signals presented, it can be seen that the capacitive ECG of all the subjects has amplitudes on the same order of magnitude, varying from 2 to 5 V. The Medlab device, adjusted to the lowest gain, also provided similar amplitudes among subjects. An exception was encountered on the elder subject whose ECG had larger amplitudes. Hence, deeper evaluation of middle-aged and elder subjects is needed.

The youngest subject presents some baseline oscillations due to its breathing cycle, to which the commercial device is less sensitive. The segment of the tallest subject presents a portion of signal acquired while talking, again with the direct contact solution being less sensitive to this fact. The shortest subject presents small T waves in the capacitive version, while the direct contact shows a regular T wave. This is a problem detected only on this subject and may be due to the relative position of the sensor on his back.

3.2 Treadmill tests

A test session was made for one volunteer on a professional gym treadmill with variable speed and inclination, Pulse Fitness 260FT.

Fourteen combinations of speed and inclination were experimented, as indicated in Table I. For each combination, a 5 minutes recording was made. In routine wheelchair use a few km/h are achieved, so 7 km/h is above the limits, and was the maximum speed tested. Regarding inclination, Portuguese law (DL 163/2006) establishes a maximum inclination of 6% to ramps serving as access to buildings. Testing up to 4.4% is near the maximum allowed, thus a demanding scenario.

Table I. Inclinations and speeds tested with the wheelchair in the treadmill

Speed [km/h]	Inclination [%]
1	0; 1.1; 2.2; 3.3; 4.4
3	0, 1.1, 2.2, 3.3, 4.4
5	0; 4.4
7	0; 4.4

The RMS value of each second of recording was computed. Then its mean value was removed, so that the continuous components present in the Medlab output do not affect the comparison. Finally, there was a normalization step to allow comparison of different amplitude ECGs. Fig. 5 illustrates the results. Regarding signal artefacts generated by wheelchair motion, it was found that the capacitive ECG presents an amount of artefacts alike to the amount observed in the direct contact solution.

Direct contact ECG RMS value is relatively more stable than capacitive coupled ECG, as visible in Fig. 5 top left graph. However, as seen in previous figures, the direct contact output is much smaller than the capacitive coupled, so the disproportion in case of artefact is much higher. After normalization the zones without artefact seem more stable, as visible in the bottom left graph.

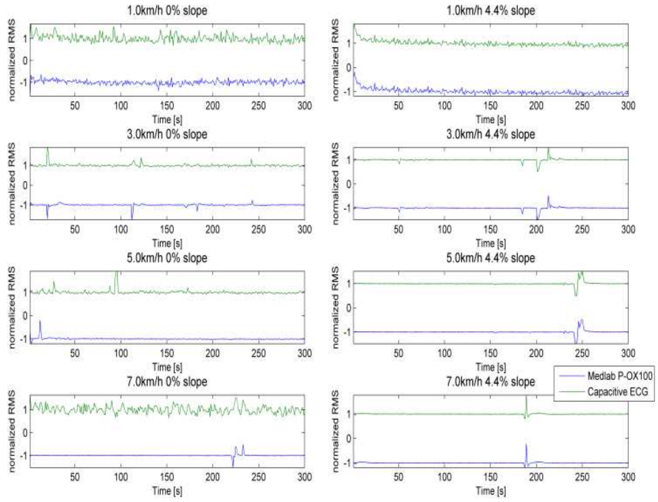

Fig. 5. Normalized RMS value of ECG signals acquired from one subject at four different speeds and two different inclinations, for the wheelchair in the Pulse Fitness 260FT treadmill. Each graph shows data from Medlab P-OX100 (blue, lower position within graph) and capacitive ECG (green, upper position). To improve readability the signals were shifted upwards and downwards.

Figures 6 and 7 depict a ten seconds period of the some recordings for speeds of 1, 3, 5 and 7 km/h and inclinations of 0% and 4.4%. The signals displayed are the reference commercial device ECG and the signal from the capacitive ECG acquired from the backrest. In these figures it is seen the hardware ability to maintain the acquisition of the capacitive ECG. The QRS peak is evidently synchronized, while only for 5 km/h the minor waves are indiscernible. Therefore, the movement of the wheelchair, even at relatively fast speeds, in the smooth floor of the treadmill, is not impeditive of good quality capacitive ECG acquisition.

4. CONCLUSIONS

Capacitive electrocardiogram sensing hardware was developed and embedded in a wheelchair. The sensing method is based on two rectangular copper electrodes, placed approximately in the direction of the scapulas. In the back of the electrodes a large copper plane with a reference signal, acts as a third capacitively-coupled electrode.

Assessment tests with eight healthy subjects normally-dressed, in a motionless scenario showed good agreement between direct contact and contactless ECG. Five minutes of recording were made to each, and the amount of artefacts present in both signals is perfectly comparable.

Tests were also conduced for the wheelchair moving in a treadmill with a volunteer. It was seen that the capacitive ECG waveform is still comparable to the direct contact solution, and that it has a similar amount of movement artefacts, for several realistic speeds, between 1 and 7 km/h, and inclinations, 0 to 4.4 %.

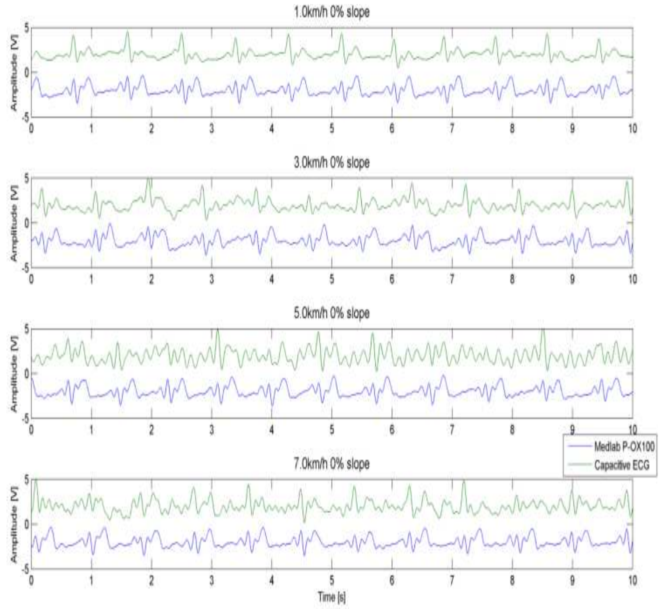

Fig. 6. ECG signals acquired from one subject at four different speeds with the wheelchair in the Pulse Fitness 260FT treadmill, running horizontally. Each graph shows ECG from Medlab P-OX100 (blue, lower position within graph) and capacitive ECG (green, upper position). To improve readability the signals were shifted upwards and downwards.

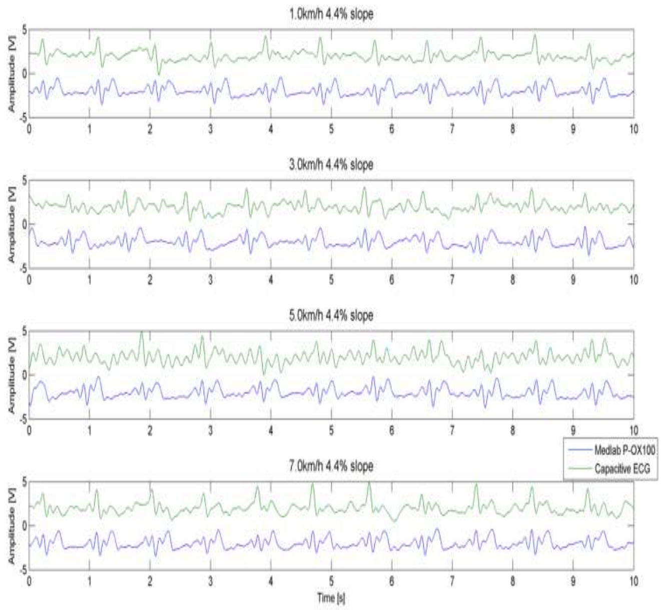

Fig. 7. ECG signals acquired from one subject at four different speeds with the wheelchair in the Pulse Fitness 260FT treadmill, with a 4.4% slope. Each graph shows ECG from Medlab P-OX100 (blue, lower position within graph) and capacitive ECG (green, upper position). To improve readability the signals were shifted upwards and downwards.

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