Off-the-Person Electrocardiography

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Abstract: Electrocardiography (ECG) methods are still mostly bound to hospital and short-time data acquisition settings. Still, a paradigm shift is emerging, in which everyday technology is increasingly capable of measuring ECG signals in a more pervasive manner. This is paving the way for systems that can better analyze and adapt to perceived changes in the health status or behavior of the user. In this paper we present a taxonomy for the intrusiveness of ECG data acquisition systems, describe a sensor design for what we call the ”off-the-person” approach, and provide a discussion of the main challenges posed by these new methodologies. Our work is targeted at pervasive electrocardiography through signal acquisition at the hand palms or fingers, by providing a simplified sensor setup that can be integrated into virtually any object with which the person interacts with. Experimental results show that data acquired using our proposed approach is highly correlated with data obtained through conventional methods.

1 INTRODUCTION

The first practical implementation of what we known today as Electrocardiography (ECG) appeared around 1887 and is credited to Augustus Waller, a British physiologist that was able to record the electrical activity of the human heart using non-invasive methods, and provided the first known systematic approach to the study of the electrical properties of the heart (Besterman and Creese, 1979). Questions surrounding the clinical applicability of the signals and limitations of the measurement instrumentation used at the time made the ECG have a slow start. It was not until 1906 that a more widespread acceptance and use occurred. The groundbreaking work by Willem Einthoven provided significant advances both in terms of the measurement methods and signal characterization, enabling the ECG to be more clearly understood. His work was recognized in 1924 through the Nobel Prize in Medicine, several years after the initial experimentations in the field (Barold, 2003).

Nowadays, the ECG is a perfectly established and mainstream technique, and it provides vital information for the diagnosis and observation of a wide array of complex cardiovascular problems that include arrhythmias, myocardial ischemia, prolonged QT interval, among many others (Drew et al., 2004)(Chung, 2000). Most importantly, early detection of changes in the cardiac patterns is crucial to anticipate severe and long lasting problems, and to develop preventive clinical interventions. Standard clinical practices are still based on short-term ECG data; the most widespread approach is the 12-lead ECG for momentary assessment in a clinical setting ($\sim$ 1 minute of data), and in selected cases, Holter monitors are used for $\sim$ 24 hour assessment in an ambulatory setting.

In this paper, we present a taxonomy for the intrusiveness of ECG data acquisition methods, together with an off-the-person sensor design targeted at data acquisition in a pervasive framework. Our work was not devised with the purpose of replacing existing data acquisition procedures. Instead, our goal is to complement current practices with a simplified sensor setup that can be introduced in multiple aspects of the everyday life of patients or even of healthy subjects, as a way of enabling a more comprehensive assessment of cardiovascular parameters, and potentiating preventive interventions. The rest of the paper is organized as follows: Section 2 describes a taxonomy for the intrusiveness of ECG data acquisition approaches; Section 3 describes our off-the-person sensor approach, highlighting the main technical options; Section 4 provides an experimental comparison between the off-the-person approach and medical-grade equipment; and finally, Section 5 outlines the main conclusions.

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2 A TAXONOMY FOR ECG DATA ACQ. INTRUSIVENESS

Given the bioelectrical nature of the cardiac activity, the voltage potential differential is the most commonly used ECG measurement principle. Still, other approaches can be used to sense the cardiac activity, such as capacitive and mechanical methods. Despite the underlying operating principle, several devices have emerged over the years, that enable ECG signal acquisition, and which we have classified according to the intrusiveness level of the hardware setup with respect to its placement on the body of the user. Figure 1 shows an overview of our taxonomy.

2.1 In-the-Person

Devices is this category are placed inside the body of the person, and are generally used only in extreme clinical scenarios to monitor or address medical conditions. The devices are surgically placed inside the body with measurement leads attached directly to the heart, enabling the continuous monitoring of its behavior and the delivery of electrical impulses whenever a deviation from a normal cardiac pattern is detected. Nowadays, most devices enable the external access and remote monitoring of basic parameters both by clinicians and patients.

One class of devices are the ***Implantable*** systems, of which artificial cardiac pacemakers are the most widely known example; these are used to compensate for shortcomings of the electrical conduction system of the heart, due to degenerative or pathological conditions (Timperley et al., 2008). Modern implantable devices can have extremely compact and lightweight form factors, an example of which is the HD-X11 system from Data Sciences International[1], with 2.2 g and a volume of just 1.4 cm^3.

Another class of devices can be defined as ***Minimally Invasive***, which includes implantable loop recorders (ILR); albeit being placed inside the body of the person, these are only applied subcutaneously, through a simple medical procedure that typically only requires local anesthesia, and enable the continuous recording of the cardiac activity.

2.2 On-the-Person

The most common approaches to ECG measurement used nowadays work by attaching a device, or some of its components, externally to the body surface. Currently, devices designed to be used in an on-the-subject approach are perfectly commoditized, and range from medical-grade equipment to personal use and self-monitoring devices for heart rate assessment in sports and wellbeing activities (e.g. Polar WearLink+[2]).

Standard ECG devices can be classified as ***Stationary*** systems. Devices in this category are typically characterized by workbench and bedside monitors for medical use, and require the placement of 12 or more leads mounted on the chest and limbs, although configurations with a lower number of leads can also be found. Other properties of these devices include the fact that they generally need conductive paste or gel to lower the skin impedance, and that the patient is bound to a limited physical space.

New developments in signal acquisition technologies greatly improved the usability, and enable more practical approaches that fall into the class of ***Ambulatory*** systems. In the clinical domain, Holter monitors are used for ambulatory cardiac assessment. These are devices in which less measurement leads are used, and a partial recording of the activity of the heart is made in an internal memory, typically over the course of 24 hours. Recently, there has also been an increasing interest in integrating ambulatory ECG sensing into portable devices, as shown by the EPI Life "Doctor in Your Pocket"[3], claimed to be the first ECG-enabled mobile phone, and also by the AliveCor[4] monitor, proposed as a clinical diagnosis tool, and which enables real-time ECG measurement on the iPhone/iPad when the subject places the accessory on the chest.

Within ambulatory systems, a vast amount of work has been done around t-shirt and other wearable form factors, such as the VitalJacket from BioDevices [5]. Another smart t-shirt is evaluated in (de Isla et al., 2011), in which the measurement leads are embedded into the fabric as a way of achieving a more practical acquisition setup. In (Chi et al., 2010), the authors present a comprehensive review of capacitive sensor technologies that can be applied to a chest strap or t-shirt to monitor the cardiac activity. A wearable device designed as a necklace is described in (Silva et al., 2011b), which uses dry Ag/AgCl electrodes and enables heart rate measurement on the user's neck.

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[1] http://www.datasci.com/products/implantable-telemetry

[2] http://www.polar.com/en

[3] http://epimhealth.com.sg

[4] http://www.alivecor.com

[5] http://www.biodevices.pt

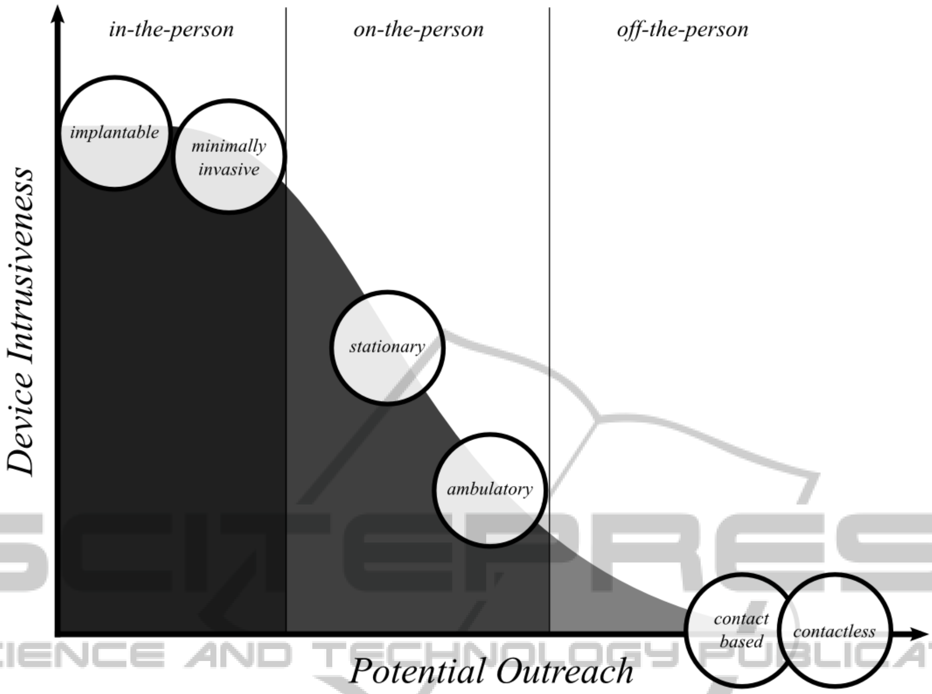

Figure 1: Overview of the intrusiveness and potential outreach of ECG data acquisition systems.

2.3 Off-the-Person

One of the challenges that has recently started to be more prominently addressed in the state-of-the-art, is the improvement of the sensor acceptability into what can be defined as an off-the-person approach, given that the sensors are integrated in objects with which the subject regularly interacts with. The rationale behind this approach is that, unlike the on-the-person methods, in which the user needs to wear the sensor or perform a voluntary action to have the sensor in contact with his body, in this case the sensor is integrated in a pervasive manner, so that the user does not need to change his/her normal interaction patterns.

Within this trend, one of the categories comprises ***Contact Based*** systems. An example can be found in previous work by our team (Silva et al., 2011a), where a bipolar sensor with virtual ground and dry electrodes was proposed for ECG data acquisition at the hand palms or fingers. The main advantage is that these methods can be easily integrated into everyday items without impacting on the user's routines. Applications for such devices include ECG monitoring while the person is working at a computer keyboard, holding a game station controller, the steering wheel of a car, and many others items, enabling its use in a pervasive electrocardiography framework, and promoting novel long-term monitoring paradigms.

The off-the-person approaches also comprise ***Contactless*** systems; this class includes capacitive and mechanical methods, which albeit not being capable of measuring the tradicional ECG signal, measure an ECG-like activity. Capacitive sensors measure the small time-varying electric fields associated with the bioelectric activity of the heart (Chi et al., 2010)(Martins et al., 2011). These sensors do not require direct contact with the body of the user, and can be designed to measure the ECG at distances of ~ 1 *cm* or more, even with clothing in-between the body and the sensor, enabling its integration in the back of a chair, in a car seat, or other analogous items. Mechanical sensors measure heart-related events by sensing the small vibrations propagated to the body surface after the contraction of the cardiac musculature. This technique is known as ballistocardiography or seismocardiography, and current approaches are based either on accelerometers or electromechanical films (Postolache et al., 2010).

These novel approaches are aligned with the latest trends in medical applications of technology. As Eric Topol states in his book (Topol, 2012), the future of healthcare will inevitably lie on the infiltration of medical devices into our daily lives, collecting more data about the human being over longer periods of time, and reasoning about these large volumes of data. This is the very essence of pervasive health.

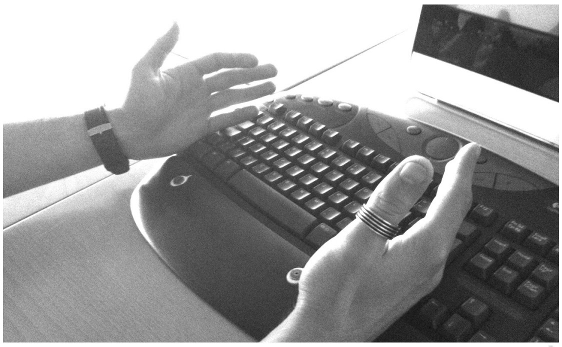

Figure 2: Contact based off-the-person sensor integrated in a standard computer keyboard.

3 A CONTACT BASED SENSOR FOR OFF-THE-PERSON ECG

In our work, we have been focusing on minimizing the number of electrical contact points with the subject's body, eliminating the need of any gel or conductive paste in the interface with the skin, and devising a non-intrusive sensor system. Figure 2 shows an example of our sensor integrated in a computer keyboard. Our tests have shown that even when compared with conventional approaches in which pregelled electrodes are used, this configuration provides an output signal with adequate quality both with dry Ag/AgCl or conductive textile electrodes, and no skin preparation in either case.

3.1 Sensor Design

We developed analog signal conditioning circuitry adapted to the ECG in terms of gain and bandwidth (Malmivuo and Plonsey, 1995). Our design is single-ended and is based on the classical voltage potential differential principle, one singularity being the fact that the typical ground electrode is replaced by a reference voltage produced by the circuit (generally referred to as the "virtual ground"). Table 1 shows the typical physiological specifications for ECG signals (Webster, 2009); to measure the low potential differences associated with these signals (in the mV range), our sensor design includes a precision instrumentation amplifier (In-Amp) offering high common-mode rejection (110 dB at gains greater or equal than 10). Furthermore, we use low-noise high speed operational amplifiers (Op-Amp) to perform bandpass filtering and amplification.

Table 1: Specifications of the ECG.

Range	Frequency
$0.5-4\ mV$	$0.01-250\ Hz$

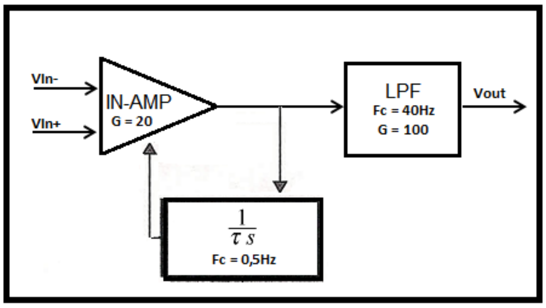

Figure 3: Block diagram of the ECG sensor design.

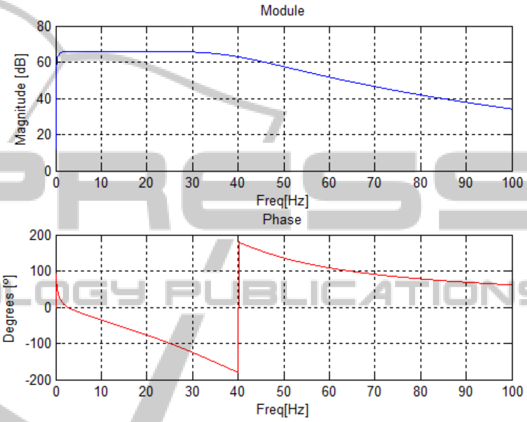

Figure 4: Frequency response of the ECG sensor block.

A block diagram of the circuit is shown in Figure 3. The use of dry electrodes introduces a higher impedance and is more prone to high frequency noise; as such, our design uses a gain of 2000 and a bandwidth between 0.5-40 Hz. We have a first amplification stage that uses an instrumentation amplifier with gain 20, to measure the weak voltage potential differences produced by the cardiac activity and increase their amplitude. Afterwards, an active 1st order high-pass filter (Gain = 1; Cutoff = 0.5 Hz) is applied in order to minimize the impact of low frequencies; in particular to remove modulation introduced by the respiratory activity. Finally, we use a 4th order Butterworth low-pass filter (Gain = 100; Cutoff = 40 Hz), to limit the bandwidth of the signal to a range that discards the powerline noise, and to further increase the amplitude of the signal in order to obtain higher definition in the digital domain. The frequency response of the sensor is presented in Figure 4.

Although our sensor was specifically designed for 1-lead differential measurement at the fingers or hands (left / right) with virtual ground, it can also be used in standard chest or limb locations, with the option to use a ground lead as well. Equation 1 shows the transfer function for this sensor (V_{ss} denotes the reference voltage).

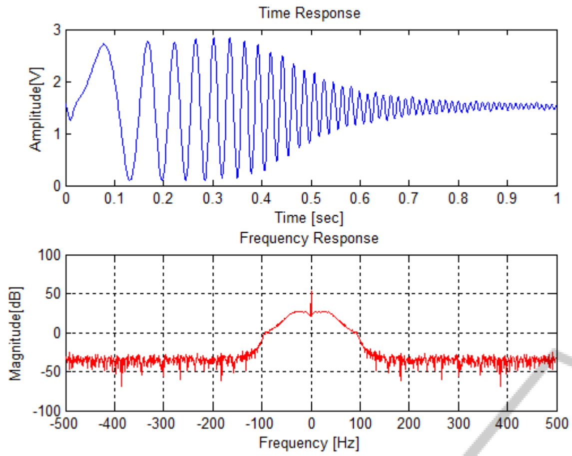

Figure 5: Time and frequency response of the ECG sensor to the chirp signal.

$$V_{Out} = (V_{In+} - V_{In-}) \times 2000 + V_{ss} \qquad (1)$$

3.2 Experimental Characterization

Tests were performed to characterize the quality of the analog front-end in terms of Signal-to-Noise Ratio (SNR), Signal-to-Noise Ratio plus Distortion (SINAD), and Total Harmonic Distortion (THD). In all experimental tests, the signals were generated using an Agilent 33220A function generator, and acquired using an analog-to-digital converter (ADC) with 10-bit resolution, a sampling rate of 1000 Hz, and a 3.3 V peak-to-peak dynamic range (V_{pp}) (Guerreiro et al., 2013). The function generator used in our experiments is not able to accurately generate waveforms in the near-millivolt range, and as such, to characterize the real response of the analog circuit, we reduced its gain to 100 (Gain = 1 at the In-Amp), ensuring an output signal between $0-3.3\ V$, that is, within the dynamic range of the ADC.

Table 2: Dynamic specifications.

SNR [dB]	SINAD [dBc]	THD [dBc]
44.54	42.49	-46.74

For this test we injected a synthesized chirp wave spanning the $0-100\ Hz$ frequency range, with 1 second duration, 28 mV peak-to-peak, and offset of $V_{cc}/2$ (V_{cc} being the supply voltage). Figure 5 shows the frequency response of our ECG circuit; as shown in the top figure, the output signal of the circuit is a chirp wave with $\approx 2.8\ V$ peak-to-peak (V_{pp}) and with attenuation in the low and high frequencies, a natural response of the bandpass filter that we have used. To characterize the dynamic specifications of the circuits, we used a synthesized sine wave with a frequency of 24 Hz, 28 mV peak-to-peak (V_{pp}), and offset of $V_{cc}/2$; in Table 2 we summarize the results.

4 MEDICAL-GRADE VS. OFF-THE-PERSON LEADS

One of the open questions in our off-the-person approach, with acquisition at the hands, is the relation between the signals obtained with this type of sensor, and those obtained with medical-grade stationary on-the-person equipments, which are the gold standard for ECG measurement. In this section we provide a comparison of both approaches.

4.1 Methodology

We conducted experimental tests involving 8 volunteers (4 males and 4 females), in which simultaneous recordings were performed using a Philips PageWriter Trim III ECG device, and our off-the-person sensor design with data acquisition performed using the Biosignal Igniter Toolkit (BIT). The Philips equipment was used in the standard 12-lead setting (I-III, V1-V6, aVF, aVL, aVR), with conductive paste applied to each of the electrodes. Our sensor was used in the virtual ground setting with dry Ag/AgCl electrodes, and the subject was asked to hold one of the electrode leads in the right hand and the other on the left hand.

The raw data from each device was bandpass filtered using the same procedure, and all the individual heartbeat waveforms were segmented. For a detailed description of the adopted pre-processing methodology, we refer the reader to (Canento et al., 2013) and references therein. We focused on determining the morphological similarity between individual heartbeat waveforms collected using each of the sensor devices. Given that dry electrodes are used in our sensor, and also due to the fact that the on-the-person equipment uses leads scattered through different anatomical locations, the amplitude of the signals collected by each device is affected by a variable scale factor. To account for such differences, in this study we adopted the cosine distance as similarity metric (Equation 2).

$$D_{cos}(x_i, x_j) = 1 - \frac{\sum_{k=1}^{n} x_i[k] x_j[k]}{\sqrt{\sum_{k=1}^{n} x_i[k]^2 \sum_{k=1}^{n} x_j[k]^2}}. \qquad (2)$$

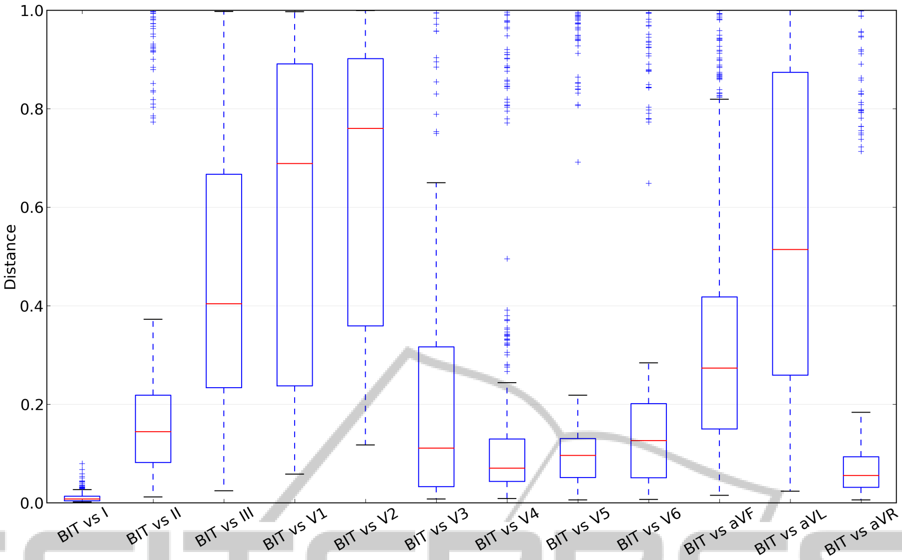

Figure 6: Boxplot of the distance between the off-the-person and each of the medical-grade leads.

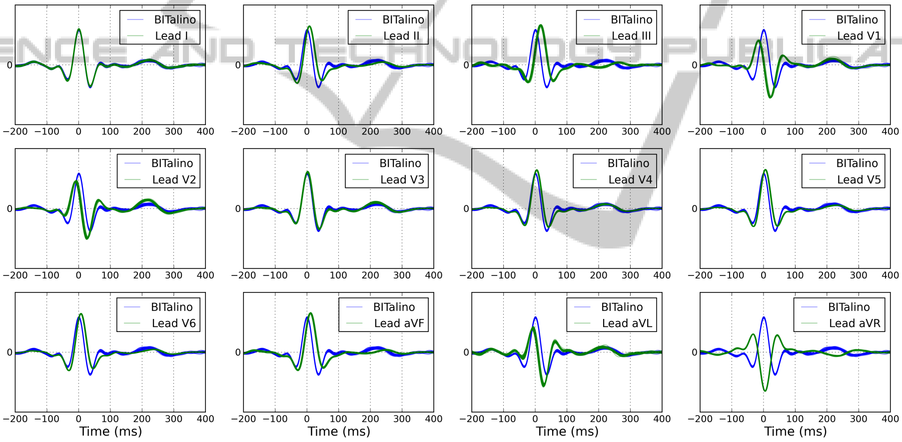

Figure 7: Example of the segmented heartbeat waveforms obtained with the off-the-person and each of the medical-grade leads for one of the tested subjects.

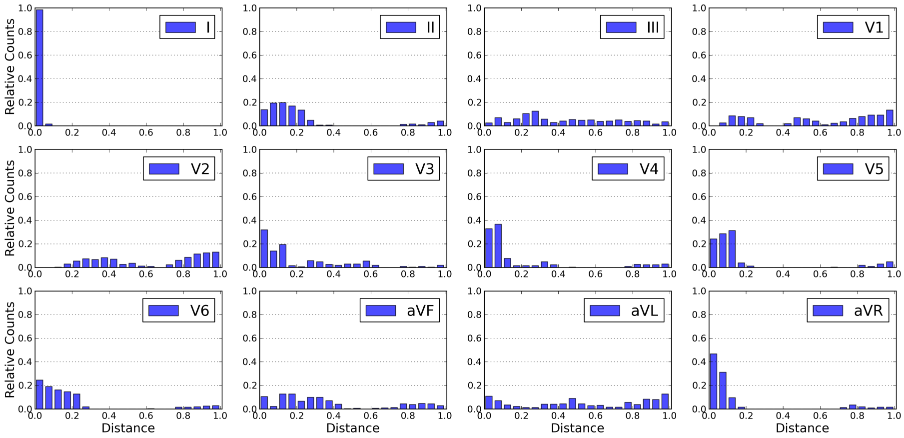

Figure 8: Histograms of the waveform distance between the off-the-person and each of the medical-grade leads.

4.2 Results

As shown in Figure 6, the signal obtained with our off-the-person approach is clearly a lead I derivation. The average cosine distance of nearly zero between the off-the-person waveform and the lead I waveform of the medical-grade device, together with the low standard deviation across the overall set of subjects, allow us to conclude that both signals are fully correlated. This is further reinforced by the visual observation of the data; in Figure 7 we depict an overlay with the segmented individual heartbeat waveforms for one of the tested subjects. The off-the-person data is represented in blue, while the on-the-person data for each of the leads is represented in green; in this case, the off-the-person lead and the lead I data present an almost exact match.

Analyzing the case-by-case statistics, we are able to observe that for some of the subjects, leads II, aVF, aVR, and V3-V6 also exhibit a low average distance to the waveform obtained using the off-the-person approach, and hence a high morphological similarity. For example in Figure 7, V3 and V4 are quite similar to the off-the-person lead. The distributions of the individual distances between our off-the-person lead and each of the medical-grade leads for the overall population can be found in Figure 8.

5 DISCUSSION AND FUTURE WORK

Electrocardiography (ECG) has progressed a long way since it was first introduced in the clinical practice. In the recent years, an increasingly growing community has focused on improving the usability of ECG equipment, and while most of the work has been targeting wearable form factors (e.g. t-shirts), our work has been pivoting towards what can be classified as an off-the-person approach. In this paper we have proposed a taxonomy of ECG data acquisition methods with respect to their intrusiveness level, described an off-the-person sensor designed for ECG data acquisition at the hands and fingers using dry electrodes, and provided experimental results regarding the comparison between the off-the-person approach and conventional medical-grade equipment.

Comparative tests have shown that the signals obtained through our off-the-person approach are matched to the conventional lead I derivation, and that even without skin preparation or the use of conductive paste to lower the impedance with the skin, the morphology of the heartbeat waveform can be retrieved. Our work is targeted at ECG data acquisition in a pervasive framework, by providing a simplified sensor setup that can be used for everyday monitoring. The applicability of our pervasive ECG approach is not bound to the healthcare and clinical domains, given that the ECG and derived measurements are also appealing in a wide range of emerging applications, which include self-management, affective computing (Medina, 2009) or even security (Lourenço et al., 2011)(Silva et al., 2013).

Future work will focus on further validating our approach by increasing the number of tested subjects, and also in the evaluation of contactless off-the-person approaches targeting the evaluation of the relation between the signals obtained using such methods, and the signals obtained using conventional methods.

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REFERENCES

Barold, S. (2003). Willem Einthoven and the birth of clinical electrocardiography a hundred years ago. *Card. Electrophysiol. Rev.*, 7:99–104.

Besterman, E. and Creese, R. (1979). Waller - pioneer of electrocardiography. *British Heart Journal*, 42:61–64.

Canento, F., Lourenço, A., Silva, H., Fred, A., and Raposo, N. (2013). On real time ECG algorithms for biometric applications. In *Proc. of the 6th BIOSIGNALS Conf.*

Chi, Y., Jung, T.-P., and Cauwenberghs, G. (2010). Dry-contact and noncontact biopotential electrodes: Methodological review. *IEEE Rev. Biomed. Eng.*, 3:106 –119.

Chung, E. K. (2000). *Pocketguide to ECG Diagnosis*. Blackwell Publishing.

de Isla, L. P., Lennie, V., Quezada, M., Guinea, J., Arce, C., Abad, P., Saltijeral, A., Carolina, N., Crespo, J., Gonzálvez, B., Macia, A., and Zamorano, J. (2011). New generation dynamic, wireless and remote cardiac monitorization platform. *Int'l Journ. of Card.*, 153(1):83–85.

Drew, B. J., Califf, R. M., Funk, M., Kaufman, E. S., Krucoff, M. W., Laks, M. M., Macfarlane, P. W., Sommargren, C., Swiryn, S., and Van Hare, G. F. (2004). Practice standards for electrocardiographic monitoring in hospital settings. *Circ.*, 110(17):2721–2746.

Guerreiro, J., Martins, R., Silva, H., Lourenço, A., and Fred, A. (2013). BITalino: A multimodal platform for physiological computing. In *Proc. of the 10th ICINCO Conf.*

Lourenço, A., Silva, H., and Fred, A. (2011). Unveiling the biometric potential of Finger-Based ECG signals. *Comp. Intel. and Neuroscience*, 2011.

Malmivuo, J. and Plonsey, R. (1995). *Bioelectromagnetism: Principles and Applications of Bioelectric and Biomagnetic Fields*. Oxford Univ. Press.

Martins, R., Primor, D., and Paiva, T. (2011). High-Performance groundless EEG/ECG capacitive electrodes. In *Proc. of the 6th IEEE MeMeA*, pages 503–506.

Medina, L. (2009). Identification of stress states from ECG signals using unsupervised learning methods. Master's thesis, Univ. Técnica de Lisboa, Inst. Sup. Técnico.

Postolache, O. A., Girao, P. M. B. S., Mendes, J., Pinheiro, E. C., and Postolache, G. (2010). Physiological parameters measurement based on wheelchair embedded sensors and advanced signal processing. *IEEE Trans. Instrum. Meas.*, 59(10):2564–2574.

Silva, H., Lourenço, A., Canento, F., Fred, A., and Raposo, N. (2013). ECG biometrics: Principles and applications. In *Proc. of the 6th BIOSIGNALS Conf.*

Silva, H., Lourenço, A., Lourenço, R., Leite, P., Coutinho, D., and Fred, A. (2011a). Study and evaluation of a single differential sensor design based on electrotextile electrodes for ECG biometrics applications. In *Proc. of the 10th IEEE Sensors Conference*, pages 1764 – 1767.

Silva, H., Palma, S., and Gamboa, H. (2011b). AAL+: Continuous institutional and home care through wireless biosignal monitoring systems. In *Handbook of Digital Homecare*, volume 3, pages 115–142. Springer.

Timperley, J., Leeson, P., Mitchell, A., and Betts, T. (2008). *Cardiac Pacemakers and ICDs (Oxford Specialist Handbooks in Cardiology)*. Oxford Univ. Press.

Topol, E. (2012). *The Creative Destruction of Medicine*. Basic Books.

Webster, J. G. (2009). *Medical Instrumentation Application and Design*. Wiley.