MULTIPARAMETER SINGLE LOCUS INTEGRATED MULTILAYER POLYMER MICROSENSOR SYSTEM

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Abstract: Miniaturization and microintegration is well known for their potentials in providing microsystems and sensors with unmatched performance, reliability, and lower costs. Current technologies in implementation of microsensors, however, span a large variety of platforms. It is thus common for microsensors measuring differing parameters to exist on different combinations of substrates, not to even mention the associated signal conditioning, processing, and data communication electronics. It remains a challenge to integrate multiple sensors with complex electronics into a single high-density microsystem, particularly for certain applications in medical diagnostics and healthcare, where mechanical flexibility of the substrate and biocompatibility also becomes crucial considerations. Traditional microintegration technologies such as system-in-package, system-on-chip, and advanced assembly and packaging, may often be inadequate. A mutliparameter single locus integrated multilayer polymer microsensor system is proposed to address the fundamental issues of high-density integration, flexibility, biocompatibility, easy application, high sensitivity, and reliability for medical grade diagnostics and other physiological applications. The architecture of the multilayer system is discussed, as well, implementation and fabrication of the multisensor layer is demonstrated, and the results on performance discussed.

1 INTRODUCTION

Miniaturization and microintegration of sensors through novel microelectronics and microelectromechanical systems (MEMS) technologies have demonstrated large potentials in providing unmatched performance, reliability, and cost effectiveness (Wang, 2002) over the recent years in many applications. Particularly, in applications involving physiological monitoring and healthcare, microintegrated sensors have been able to provide the combination of high analyte sensitivity, electrical responsiveness, precise temporal control, small feature sizes, and low power consumption, that otherwise is often very difficult to achieve through traditional technologies (Richards Grayson, 2004).

Current technologies in miniaturization of sensors span a large domain. Much research has focused on microfabrication of sensors through microelectronics and MEMS (Richards Grayson, 2004). Methods in fabrication include various lithographic techniques, stereolithography, lithographie galvanoformung abformung (LIGA), and micro injection molding, to just name a few. Processes are often different and specific to each type of microsensor. As a result, integration of various microsensors and microelectronics is difficult.

Thus far, technologies for microintegration include system-on-chip (SoC) (Kundert, 2000), system-in-package (SiP) (Matthews, 2003), and advanced assembly and packaging (Fraunhofer Institut Zuverlassigkeit und Mikrointegration). SoC concepts allow designers to combine sensors and system electronics on the same substrate, on a single chip. An example is the popular lab-on-chip technologies (Pai, 2001); however, often in biological and environmental applications, it is inherently difficult to design sensors on the same substrate as the remaining electronic system (Zhang, 2007). SiP technology provides integration of multiple sensors and system electronics from differing substrates at the board level. Commonly, unpackaged chips are placed and connected on one single substrate or printed circuit board (PCB). This

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allows for a high-density integrated system, but is often limited by its rigid integration substrate, and board 'real-estate'.

In this paper, a multiparameter single locus microintegrated sensor system is proposed for, but not limited to, cardiac physiological signal acquisition in diagnostics and health monitoring. This novel integration technology platform proposes higher density integration through multilayering of mechanically flexible polymer substrates, while providing a thin flexible profile for skin tissue conformity. A complete system including multiple microsensors, filtering, digitization, processing, and communication electronics is proposed. In this manner, the microintegration platform provides advantages of high sensitivity, high actuation-to-sensor coupling, and noise reduction through local filtering and immediate digitization, for a system that can provide medical diagnostic grade precision, yet is flexible, compact and robust.

One particular implementation includes a surface biopotential electrode integrated along with a MEMS 3-axis accelerometer and signal filtering electronics all together forming the multiparameter sensor layer of the multilayer system. In this implementation, parameters of interest include electric potential and motion of the heart, recorded simultaneously, in what is known as ballistoelectrocardiography (BECG).

2 MULTIPARAMETER SENSOR SYSTEM ARCHITECTURE

The multiparameter single locus integrated multilayer sensor system consists of five functional groups (Figure 1); the multisensors, signal conditioning, microprocessor, communication terminals, and powering. Multiple sensors acquire signals of different parameters, and convert the signals to electrical outputs. The signals are conditioned through appropriate filters and amplifiers, as close to the sensing elements as possible, to minimize noise. Signals are then routed to the mixed signal microprocessor (MSP) where it is digitized, processes, and transmitted through radio or wired communication portals. The system is powered through either permanent or disposable micro-batteries.

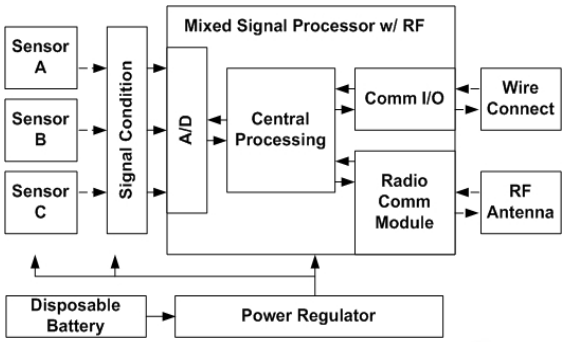

Figure 1: Modules of the integrated sensors system.

The conceptual assembly of the system is shown in Figure 2. The system consists of two layers, with option to be detachable from each other, and is connected through columnar interconnects. Each layer is composed of a flexible substrate (e.g. polyimide), on top of which the electronic system is placed and routed. Intermediate and encapsulating each layer is a flexible material (e.g. silicone) acting as insulation, structural support, and mechanical protection. The intermediate layer can be shaped and is electrically patternable such that electrical interconnects, inter-layer attachment anchors, and sensing element windows can be designed.

Here, with reference to both Figure 1 and Figure 2, the multiple sensors and signal conditioning electronics are shown on the lower layer, which allows the sensing elements to be closer to their corresponding physiological actuations. Also situated on the lower layer is a mini-connector for applications requiring wired connections. The MSP with build-in radio-frequency (RF) communication module and the RF antenna are both placed on the upper layer. Signals from the conditioning module on the bottom layer are routed to the processor on the top layer through the interconnects. Signals between the processor to and from the wired connection are also routed through the interconnects.

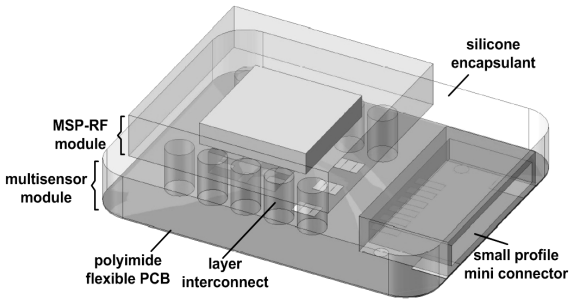

Figure 2: The multiparameter single locus integrated multilayer polymer microsensor system.

Another important part of the integrated multilayer sensor system is the attachment mechanism to a subject surface. Since the integrated multilayer sensor system is designed to be flexible, with a low profile, to conform well to the contours of human skin surface, the attachment mechanisms must not alter this feature. Figure 3 shows how the integrated multilayer sensor device is conceptually applied to a subject tissue surface by attachment of a novel disposable adhesive. This disposable adhesive must be very thin, attachable on both sides and conductive at portions where it is required.

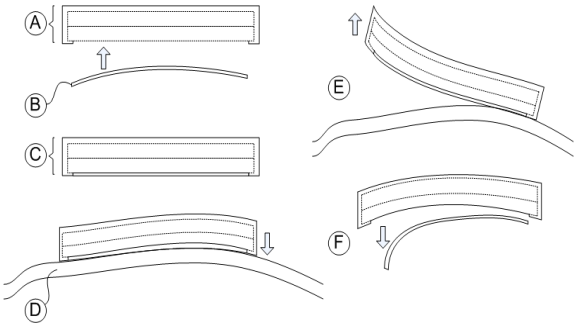

Figure 3: Application of integrated sensor device with novel disposable adhesive: The integrated sensor device (A) is attached on the bottom side with the disposable adhesive (B) forming a ready-to-apply device (C), where then it can be attached to subject skin surface (D) with high conformity. Device is removed from subject by simply pealing (E) off from attached surface, while disposable adhesive can then be removed from device (F) for hygienics.

3 IMPLEMENTATION OF MULTISENSOR LAYER

A model of the multisensor layer of the multiparameter single locus integrated multilayer sensor system has been implemented and fabricated, while the reminder of the system is underway. This paper will only discuss the implementation and fabrication of the multisensor layer.

Figure 4 shows the system blocks for the multisensor layer. Two sensor modules were included; one, a three-axis accelerometer, and the other, a single-channel surface biopotential electrode. Signal output from the accelerometer was passed through passive low-pass filtering prior to the terminal connections. There was no local filtering implemented for the electrode signal to maintain relative simplicity of the system such that focus at this stage of development can be placed on overall system integration. Power input stabilization was included to maintain optimal performance of the powered components. Input and output terminals of the multisensor layer were connected via thin wires to macro-scale connectors for testing purposes.

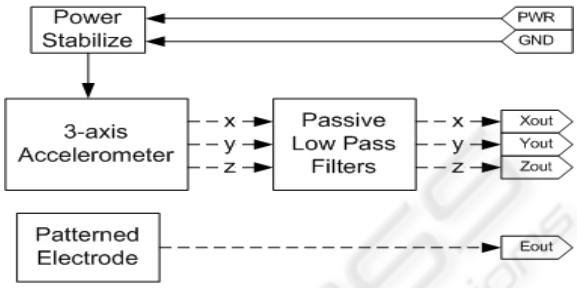

Figure 4: System blocks of the multisensor layer.

Figure 5 shows the model assembly of the multisensor layer. Base substrate of this layer was chosen to be 50-micron polyimide flexible PCB. Polyimide is a strong thermalset with excellent tear-resistance, thermal and chemical resistance (Callister, 2003). The three-axis accelerometer, filtering, and power stabilizing electronics were placed and routed on the top-side of the polyimide cell. The biopotential electrode was designed and patterned on the reverse-side of the polyimide cell, and connected to the top-side through micro-jumper wire. Alternatively, metal-plated vias through the polyimide substrate would be ideal, but to reduce model fabrication complexity and costs, jumpers were chosen. A small profile mini-connector was placed at one end of the polyimide cell for signal acquisition and testing. As will be further discussed in the next section, during model fabrication and assembly, the mini-connector was replaced with thin wires and then joined to a larger connector, again, to simplify fabrication and assembly complexity and reduce costs.

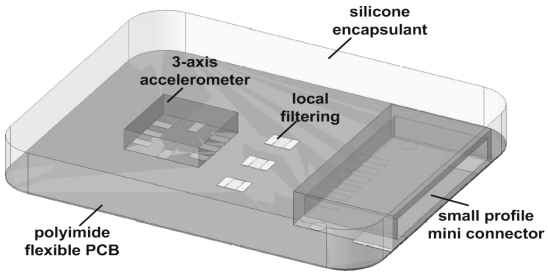

Figure 5: Multisensor layer of multilayer integrated system.

Lastly, encapsulation of the polyimide cell was chosen to be with electronic grade silicone encapsulant. Typical electronic grade silicone encapsulant provides good insulation and mechanical protection for the underlying devices while allowing for shapability. Transition to fabrication with medical grade silicone encapsulants would be straightforward because of the silicone's relatively similar compositions. Rapid prototyping moulding techniques were applied to provide the desired resulting shape. The total thickness of the entire cell was targeted at 3mm to maintain the feature of skin contour compliance.

4 FABRICATION METHOD

Fabrication and assembly of the multisensor layer could be categorized into four sections; one, fabrication of the polyimide circuit; two, device component population; three, encapsulation; and four, preparation of double-sided conducting adhesive. This paper will focus on discussions for the first two aspects of device fabrication. Since fabrication was for a set of model devices, techniques employed were mostly rapid prototyping methods with simplified steps rather than larger scale manufacturing processes.

4.1 Polyimide Circuit

Fabrication of the polyimide circuit is a standard process in the industry (Egloff, n.d.). It is also commonly known as flexible PCB circuit printing. Printing of flexible PCB circuits is provided by many fabrication houses around the world; however, due to its specialty, most orders are still costly and require large quantities not suitable for prototyping or model trials.

Fabrication was thus contracted through the Institute for Micromachining and Microfabrication Research at Simon Fraser University. Layout of the single-layer double-sided polyimide circuit was submitted electronically, for the fabrication process to be done with proprietary metal-on-polyimide rapid prototyping process.

4.2 Components and Population

Components for the model multisensor layer were carefully selected to ensure ease of assembly without elaborate processes or tools, while maintaining relatively small device profile. As a result, all electronic components used were surface mount devices with package size no greater than 5mmx5mm^2 and bonding pad pitch larger than 0.65mm. Bonding of the device was through cold soldering (silver epoxy, conductive ink) by hand. Heat soldering with temperatures greater than 200°C was too hot for the thin metal film deposited on the polyimide under the particular polyimide metallization process carried out. Alternatively, a thicker film metallization on polyimide circuit would allow heat soldering, but such was not the objective of this research.

5 RESULTS AND EVALUATION

5.1 Flexibility

A total of four devices were populated, assembled and encapsulated using the fabrication method described in the previous section. Figure 6 shows one of two devices encapsulated in 5mm thick silicone encapsulant. Although it was 2mm thicker than the 3mm that was planned, the device was flexible enough to bend up to 30° without any visible cracking or detachment between the substrate and encapsulant.

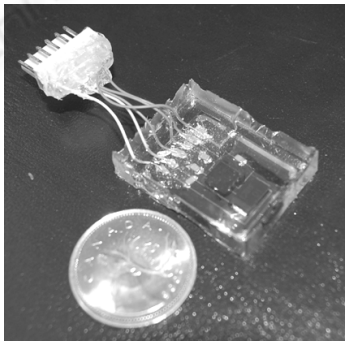

Figure 6: Encapsulated multisensor layer with macro-scale connector for testing attached, comparison with a Canadian quarter.

The remaining two of the four devices were encapsulated in 0.5mm thick silicone. Figure 7 shows one of the two devices wrapped around a finger demonstrating its flexibility. With the 0.5mm encapsulation thickness, although no quite enough to form a levelled-surface over the larger components, it was sufficient to provide electric insulation on most parts and some degree of mechanical protection. The device was able to bend up to 90° without any visible cracking or detachment between the substrate and encapsulant.

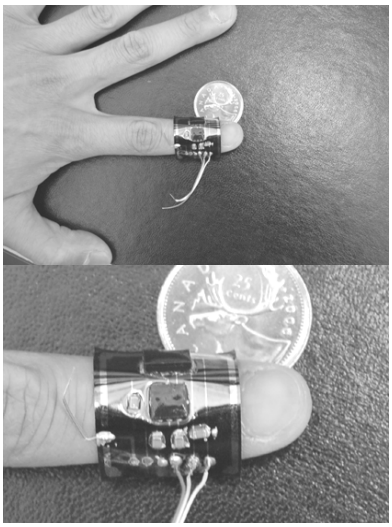

Figure 7: Thin encapsulation of multisensor layer allowing for extra flexibility; Top, sensor device wrapped around the first digit of a finger; Bottom, close-up of sensor wrapped around finger.

5.2 Size and Dimensions

The model multisensor layer devices were approximately 2.0cmx2.5cm. As can be seen in Figure 6 and Figure 7, the metal traces were relatively thick, components were relatively large, and spacing between components was maintained such that assembly by hand without any precision tools can be managed. Should the devices be populated on the substrate without the manufacturer packaging, and/or smaller footprints and traces applied, the device dimensions should be easily reduced to half the model size, say 1.0cmx1.5cm.

5.3 Comparative Functional Assessment

Initial comparative function assessment was conducted to provide quick insight into how the novel device's sensing capabilities compared to traditional devices in the particular application. The comparative assessment gave an overview of the device functional performance prior to engaging into more detailed studies of its performance characteristics, which will be topic of another discussion.

In the comparative assessment, the multisensor was applied in the same manner as traditional accelerometers on the chest of the subject in obtaining BCGs (McKay, 1999). Figure 8 shows the sensor locations and reference electrode locations for comparative study. Locations 1, 2, 3, show the various positions the sensors can be placed along the subject's sternum in recording heart motion. Ideally, sensors should be situated simultaneously at the same location for most accurate comparison, but such placement is not possible. Differences in signal outputs due to location were thus considered during the analysis. Two electrodes, *E*, approximately 2" apart were placed beside the sternum along the sternal midline to form a reference modified-ECG-lead in studying a subject's BECG.

At this stage, only the motion sensing element of the multisensor was compared with other traditional sensors. It is important to assess first whether or not the signal pickup by the integrated sensors suffers any unwanted effects due to the flexible substrate. For testing purposes, attachment of the sensors to the subject skin surface was with common off-shelf non-conducting double-sided medical adhesives.

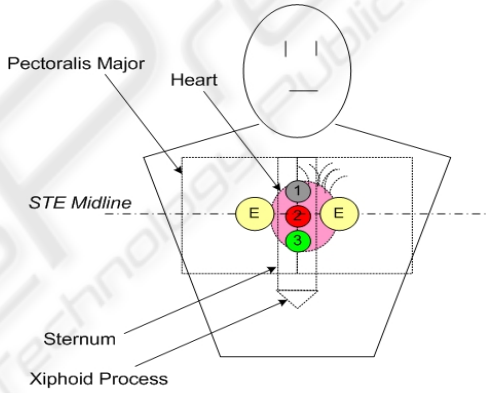

Figure 8: Sensor placement locations in comparative assessment; *E* denotes electrode locations, while *1*, *2*, *3*, denotes sensor locations.

The data acquisition system and sensor powering is shown below in Figure 9. The flexible multisensor was connected with power input, and signal output routed to filtering and amplification circuits. The conditioned signals were then passed into a data acquisition system (National Instruments DAQ) stored and analysed. Additional sensors included in the comparison were also digitized and stored through the same data acquisition system such that precise synchronization between channels recording incoming signals can be obtained. The reference electrodes were connected to a standard ECG machine (Burdick) with analog output connected to the acquisition system as the sensors were.

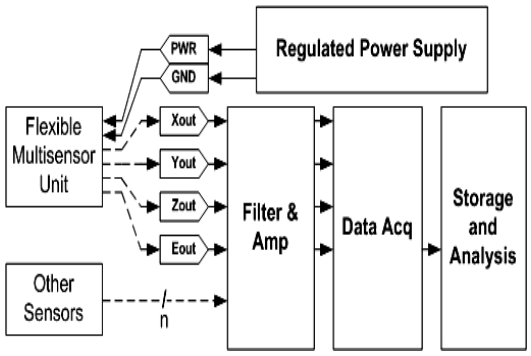

Figure 9: Data acquisition system and sensor connection setup.

Figure 10 shows the physiological signals of a single heart-cycle recorded through the acquisition system of the flexible multisensor with reference to synchronized ECG.

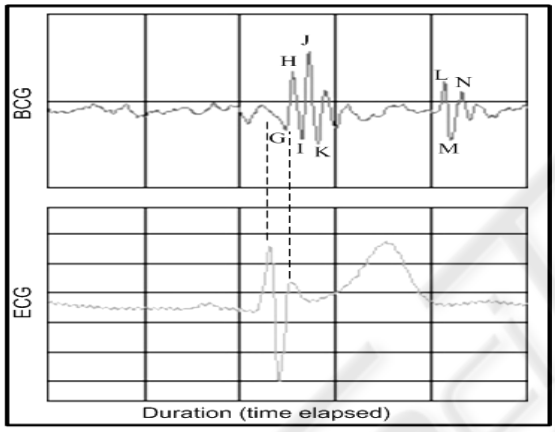

Figure 10: BCG signal of a single heart-cycle as recorded by the multisensor referenced to synchronized ECG.

As can be seen, all characteristic waveforms of a classical BCG signal, denoted by letters (H, I, J, etc.), similar to that measured through a high-precision accelerometer in McKay (1999), can be identified. Several feature extraction algorithms and physiological interpretation analysis were also developed; however, such topics were reserved for subject of a separate discussion.

A total of four comparative recordings were taken from a single subject. With a high-precision reference accelerometer (Bruel&Kjaer) fixed at location-3 (Figure 8), the flexible multisensor and a rigid sensor, housing the same MEMS 3-axis accelerometer on PCB, were rotated between location-1 and location-2. Samples were taken for duration of 30-seconds at 500Hz (each channel) over a total of four channels (3 sensors, 1 reference ECG-lead). Table 1 summarizes the recordings and the different sensor placements during each trial. From the combination of trials recorded and reference sensor comparison, the quality of signal related to sensor placement, and filtering differences can be qualitatively assessed.

Figure 11 shows a portion of the recorded signals from trial-I over a period of 2.6-seconds, or approximately three heart-beats. Channel-1 shows signal recorded from the rigid sensor, while channel-2 shows signal recorded from the flexible multisensor. Channel-3 and Channel-4 form the reference BCG and ECG signals respectively, in which the flexible sensor and rigid sensor were compared to. Although the sensitivities of the MEMS accelerometer is much lower than the high-precision reference accelerometer, it was qualitatively determined, that in general, the morphology of the BCG signals obtained from the flexible multisensor is very similar to that in the reference sensor.

Table 1: Summary of sensor recordings with location, filter, and overall sensitivity-gain indicated.

Trail	Sensor	Location	Filter	Overall Sensitivity/Gain (approx.)
I	Rigid	1	50Hz	3.0V/g
	Flex	2	100Hz	3.0V/g
	Reference	3	100Hz	9.8V/g
II	Rigid	2	50Hz	3.0V/g
	Flex	1	100Hz	3.0V/g
	Reference	3	100Hz	9.8V/g
III	Rigid	1	100Hz	3.0V/g
	Flex	2	50Hz	3.0V/g
	Reference	3	100Hz	9.8V/g
IV	Rigid	2	100Hz	3.0V/g
	Flex	1	50Hz	3.0V/g
	Reference	3	100Hz	9.8V/g

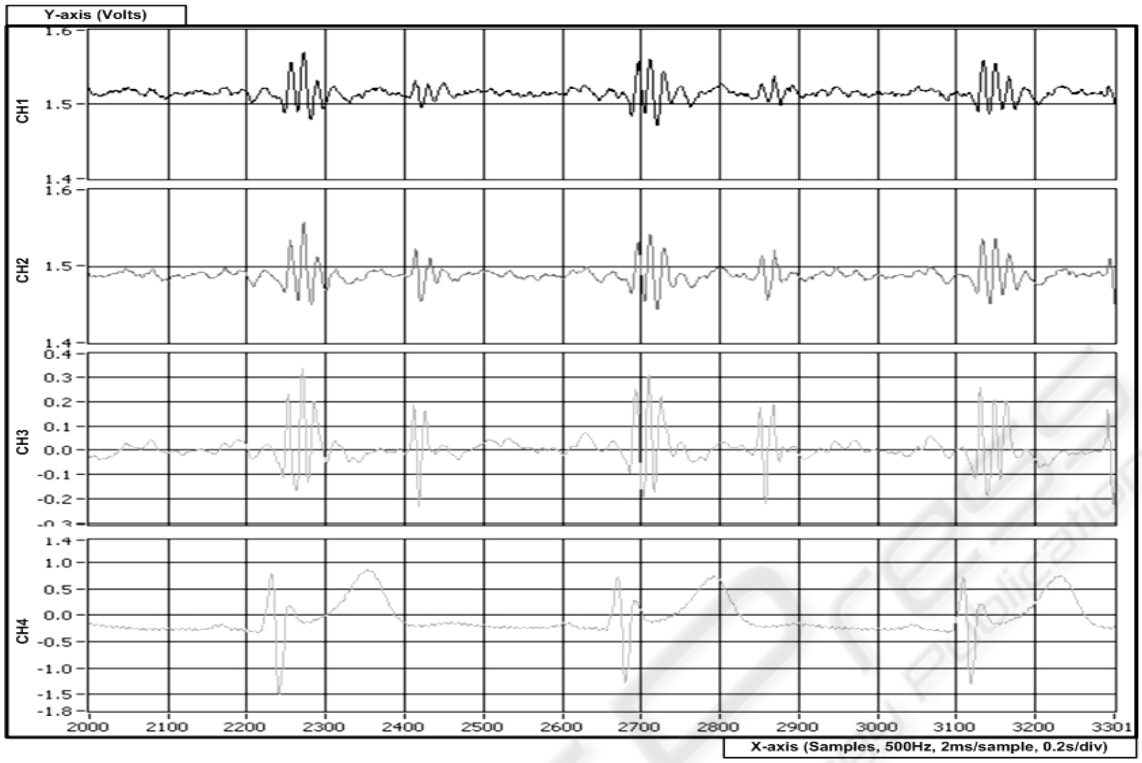

Figure 11: Portion of recording comparing novel flexible multisensor with rigid sensor and reference sensor and ECG; CH1 – rigid sensor; CH2 – flexible multisensor; CH3 – high-precision accelerometer reference; CH4 – ECG. All channels sampled at 500Hz.

Further, from trials-I and III, it was observed that altering the filtering cut-off frequencies in the signal conditioning stage did not have astonishing effects on the morphology of the signals as expected. On the other hand, situating sensors further away from the reference sensor did result in signals less similar in morphology and smaller amplitude compared to sensors closer to the reference sensor. That is to say, regardless of sensor type (rigid or flexible) and filtering cut-off frequency, a sensor placed at location-2 provided signals closer than a sensor placed at location-1 when compared to the reference at location-3. Nevertheless, the filtering and location effects observed should be subject for a more controlled study in the future.

From the qualitative comparative observations gathered, it can be concluded that first, the novel flexible multisensor provided similar functional sensitivity as the rigid PCB version housing the same 3-axis MEMS accelerometer. This was a preliminary indicator that suggested that the flexible substrate proposed in the multiparameter single locus multilayer integrated microsenor system does not inhibit the actuation-sensor coupling due to its flexibility. Next, the signals recorded from the flexible multisensor were essentially similar in morphology as the high-precision reference accelerometer. This is an indicator that the novel flexible multisensor has potential for applications in BECG with medical diagnostic grade precision, while providing a highly-integrated system in the near future.

6 CONCLUSIONS

State-of-the-art technologies in microintegrated multisensor systems were discussed. It was noted that the current systems lacked several important modules and features useful in certain specialized healthcare monitoring and medical diagnostic applications. A mutliparameter single locus integrated multilayer polymer microsensor system was proposed to incorporate high-density multisensor and microelectronics system integration on a flexible substrate platform that provides good skin conformity in physiological applications. Architecture of the proposed system was discussed, as well as the implementation and fabrication of the multisensor layer of the multilayer system. Model

devices of the multisensor layer were shown and their mechanical characteristics discussed, particularly, it demonstrated excellent flexibility for good skin conformity. It was also demonstrated that information on bodily motion due to cardiac contraction, or BCG signals, can be acquired through sensors integrated on the proposed platform. The system further shows potential for medical grade diagnostic performance. Further testing and characterization of more compact and highly-integrated models of the proposed system is under development, and will ultimately provide more insightful understanding of the effectiveness of the proposed microintegration platform.

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