A reliable signal conditioning circuit to acquire human biopotentials

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Abstract— It is well known that every human being is a complex system made up of cells, tissues, organs and organ systems that function together to maintain its health. The coordinated physiological processes maintain most of the steady states in an organism, not at a fixed value, but within a narrow, relatively constant range, known as homeostasis [1]. Recently, a non-invasive measurement of human biopotentials has been proposed in order to provide information about the condition of the human system as a whole [2]. In this work, the development of two identical signal conditioning circuits that facilitate the acquisition of the human biopotentials simultaneously from both the hands has been presented. The objective of developing these circuits is to enhance the signal levels of both the measured biopotentials uniformly and faithfully, without distortion. This is expected to enable a more reliable and detailed analysis of the acquired signals in future.

Keywords- human system, bioelectric signals, signal conditioning circuit, static and dynamic calibration, statistical analysis

I. INTRODUCTION

Human beings are complex systems [1] made up of cells, tissues, organs and organ systems that function together to maintain the health. In recent years, human beings have become more and more conscious about their health. The relatively recent growth in production of low cost portable medical devices has acted as a driving stimulus for a person to monitor several health parameters independently at home and on a regular basis. Most of these medical devices are based on non-invasive measurements of biomedical signals derived from some of the major organs or organ systems of the body [3]. It is well known that in maintaining local homeostasis, various subsystems of the human system generate bioelectric signals, and by monitoring them, the condition of that subsystem can be determined [4,5].

Recently, some researchers have been working to develop methods to monitor the homeostasis [3] of the human system as a whole. Some measurements indicative of the internal state of a human being have been stated by Aoyama et al. [6] and Y. Lin [7]. Bandopadhyay [8] has published a method for determining the integral state of any artificial or natural object for which he utilizes pulse calculation, correlation detection and other statistical analysis techniques.

Bhattacharya et al. [2] have developed a non-invasive technique to monitor the condition of the human system by measuring the bioelectric signals from the fingers of both hands of the human body. Since the effect of any vital organ or organ system is minimal at these locations, hence, the pair of signals so obtained is expected to be representative of the inherent characteristic of the total human system. From this study, it was seen that the signals obtained vary around zero and lie in the millivolt range. In order to enable a more detailed study of the variations in the signals, it is necessary to enhance the signals to a higher level. So, to record these characteristics faithfully, a signal conditioning circuit with minimal signal modulation has to be developed.

In this paper, the development, calibration and testing of two such identical signal conditioning circuits, that can be used along with the human condition monitoring system in [2], has been presented. A preliminary circuit design along with detailed stage by stage calibration results have been published in a conference [11]. Using both the circuits considered in the present work, rigorous static calibrations have been performed on the total instrumentation system for the range of possible inputs to ensure faithfulness and repeatability. Thereafter, these circuits have been

used in the instrumentation system to acquire the enhanced dynamic biopotentials. The biopotentials recorded without and using the signal conditioning circuits has then been compared to verify the reliability of the signal conditioning circuits for this particular application.

The paper has been organized as follows. The signal conditioning circuit design has been described in Section II. An analysis of the static calibration of the total instrumentation system is detailed in Section III. The dynamic calibration of the instrumentation system using the human biopotentials is stated in Section IV along with a statistical analysis of the data. A comparison of the biosignals, acquired directly and with the help of the signal conditioning circuits, is presented in Section V in order to verify the reliability of the acquisition of the biopotentials. The conclusions are stated in Section V.

II. SIGNAL CONDITIONING CIRCUIT

The schematic block diagram of the total human condition monitoring system, including the developed signal conditioning circuit, is shown in Figure 1a while the corresponding circuit diagram is shown in Figure 1b.

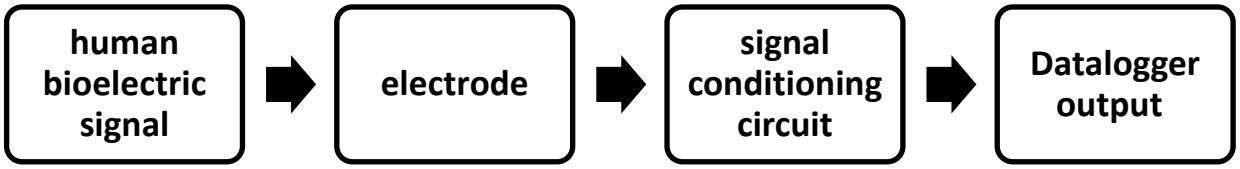

Figure 1a. Block diagram of the human condition monitoring system

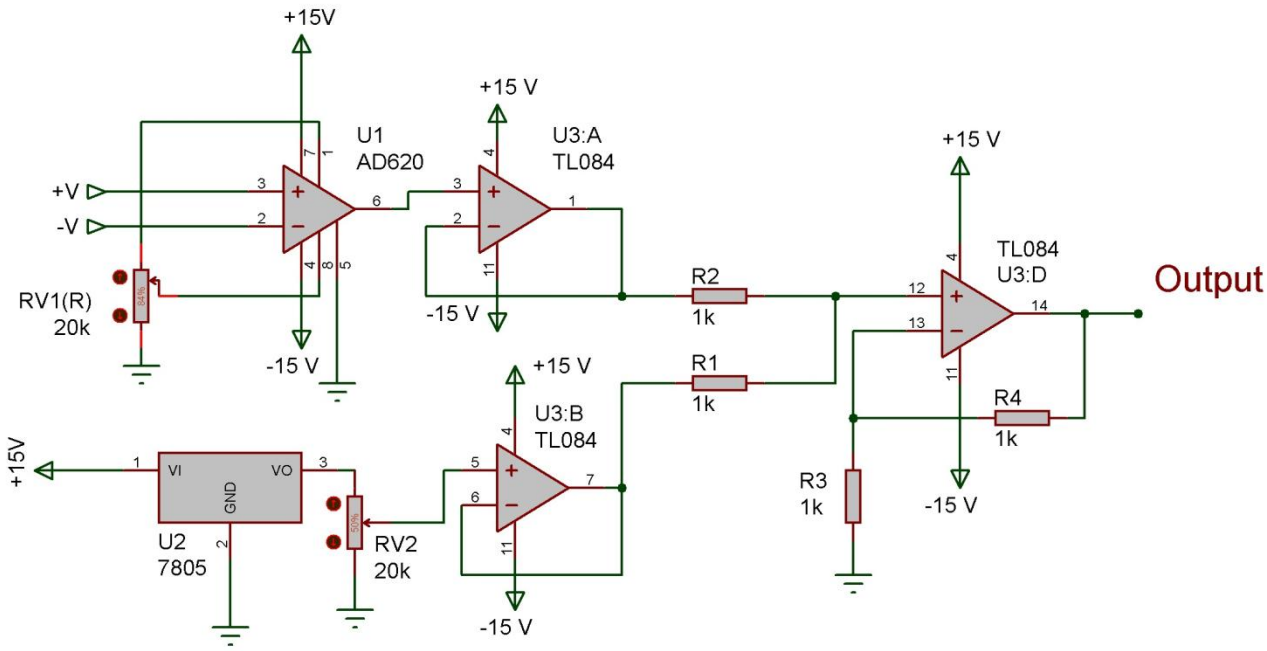

Figure 1b. Circuit diagram of the signal conditioning circuit

As observed in [2], the range of the input biopotentials is bidirectional and lies typically within -300mV to +300mV. The first objective of the signal conditioning circuit is to enhance this signal into the range [-2V, +2V]. In order to remove any dead band effects around 0V, it is further required to shift this range into a positive voltage, typically [+1V, +5V], that is, add a bias of +3V. An instrumentation amplifier chip AD620, which has high CMRR, is used for this purpose. The gain equation [9] of the AD620 is G = (49.4kΩ/RV1)+1. Here, RV1 is the external variable resistor, as shown in the circuit diagram Fig.1b, which is used to obtain the variable gain G. The amplification factor required in the present case is 6.7 and for that, the value of the resistance is theoretically calculated to be 8.67kΩ. The amplifier, denoted as U1, has a buffer in the first stage, which is followed by a differential amplifier. For introducing a bias of +3V, a 7805 voltage regulator, denoted as U2, is used which delivers a fixed positive supply voltage of +5V. This is connected to a variable resistor RV2 of 20 kΩ which is varied suitably to get the required bias voltage of +3V. Two of the amplifiers of a TL084 J-FET quad operational amplifier, marked U3:B and U3:A, are used as buffers for the bias voltage and the AD620 outputs respectively. The respective outputs are summed in the third amplifier of the TL084, marked U3:D, which is used as

the summing amplifier to give an output in the range [+1V, +5V]. So, with the help of this circuit, an input signal in the range of [-300mV, +300mV] can be suitably amplified to obtain a scaled output in the range [+1V, +5V].

III. STATIC CALIBRATION OF THE INSTRUMENTATION SYSTEM

a. Calibration results of the test circuit [11]

As stated at the outset, a preliminary signal conditioning circuit was designed and each segment of the instrumentation system as shown in Fig. 1a has been calibrated stage by stage. The overall procedures and results from that study [11] are restated here for ready reference. At each stage of the calibration, various magnitudes of dc voltages within ±300mV have been applied from a standard source (Digital Millivolt Calibrator of Libratherm make, Model-LC-05). In all these cases, Rishabh make digital multimeters (Rish Multi 18S) [12] with a sampling time of 50ms have been used along with their adapters, Rish Multi SI 232, to record the data for a typical duration of 120s and a total of 2400 data have been stored in the PC in each record.

The procedure used for the calibration is as follows. Firstly, the linearity of the AD620 outputs were tested for the total input range at various supply voltages ranging from ±9V to ±18V. Of these, the supply voltage to be used for the AD620 was fixed at a best suited value of ±15V. Thereafter, the pair of electrodes and the differential amplifier has each been calibrated separately. Then, the combination of the pair of electrodes and the differential amplifier has been calibrated, followed finally by the calibration of the total instrumentation system consisting of the pair of electrodes, the differential amplifier and the summing amplifier.

As stated in the observations in [11], it is justified to infer from this study that the electrodes have the capability of reproducing the voltage signals almost exactly with a limiting error of ±1mV, which occurs for inputs in the range of -0.3V to +0.1V. Each stage of the instrumentation system also exhibits linearity in the outputs and the total instrumentation system provides a constant amplification along with the expected bias voltage for the total input range. For the total input range, the standard deviations typically lay within 2mV upto a maximum of 9mV. The maximum deviation occurs for inputs close to +0.3V and -0.3V, which are rarely recorded as observed from the preliminary analysis in [2].

b. Calibration of the two identical circuits

On the basis of the preliminary results, two such identical circuits were developed for recording the biopotential simultaneously from both the hands of the human subjects. A pair of electrodes along with each of the circuits, that are henceforth referred to compositely as amp1 and amp2, was calibrated using similar procedures. Thus, a set of calibration readings is recorded over the total input range for both amp1 and amp2 at different magnitudes of inputs for the stipulated duration of 120s. The average of the respective outputs is calculated for each input and a straight line fit, y=mx+c, is obtained using the least squares method[10], where m denotes the gain and c denotes the bias voltage for the amp1 or amp2 output y recorded using the calibrator input x.

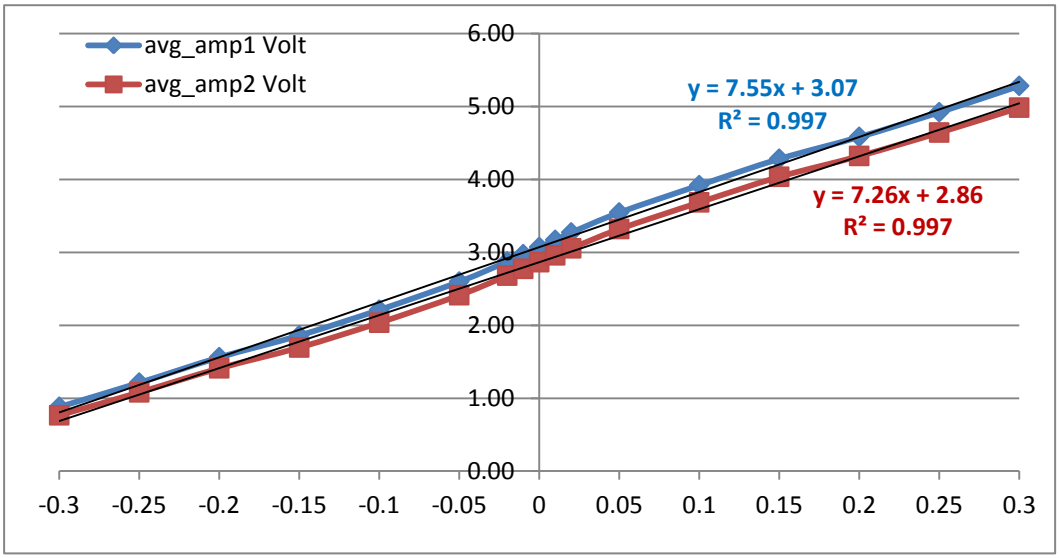

Figure 2. Output, in V, of amp1(blue) and amp2(red) for corresponding input voltages, in V

Ten such sets of readings have been recorded for both amp1 and amp2 and the corresponding plots are shown in Fig. 2 while the corresponding gain m, the bias c and their standard deviations s_m and s_c values are stated in Table 1. It is seen that the gain (m) values lie within close limits for all ten sets. The average gain values are 7.55 and 7.26 for amp1 and amp2 respectively with the goodness of fit factor being 0.997 in both the cases. The bias values are almost constant at 3.07V and 2.86V for amp1 and amp2 respectively. The reason for getting different gains for amp1 and for amp2 may be attributed primarily to the different external variable gain resistors RV1 used in both the cases and to their individual adjustments. This is also the cause for the difference in the

obtained gains (7.55 and 7.25) from the design gain of 6.7. However, it is clearly observed that all ten sets of readings for both amp1 and amp2 provide linear and repeatable measurements.

Since the gain (m) and bias (c) values are derived from recorded data, it is useful to have a measure of the possible variations for the m and c values for each set in terms of the standard deviations of m (s_m) and standard deviations of c (s_c) [10]. From the values of s_m and s_c stated in Table 1 for all ten sets of readings of amp1 and amp2, it is observed that the values are almost identical for both amp1 and amp2 indicating the reproducibility of this circuit. Assuming a Gaussian distribution and ±3s limits (99.7%), the average gain and bias value for amp1 is thus found to be 7.55±0.27 and 3.07±0.04V, while for amp 2, the corresponding values are 7.25±0.27 and 2.86±0.04V.

Table 1: Gain and bias values, with their standard deviations, of the amplified signals

	Amplifier 1 (amp1)				Amplifier 2 (amp2)			
	m	c(V)	s_m	s_c(V)	m	c(V)	s_m	s_c(V)
set1	7.57	3.07	0.087	0.014	7.28	2.86	0.087	0.014
set2	7.57	3.07	0.087	0.014	7.27	2.86	0.086	0.014
set3	7.57	3.07	0.088	0.014	7.28	2.86	0.087	0.014
set4	7.57	3.07	0.088	0.014	7.28	2.86	0.088	0.014
set5	7.55	3.07	0.089	0.015	7.26	2.86	0.089	0.015
set6	7.53	3.07	0.093	0.015	7.24	2.87	0.092	0.015
set7	7.52	3.07	0.093	0.015	7.23	2.87	0.092	0.015
set8	7.54	3.07	0.092	0.015	7.24	2.86	0.092	0.015
set9	7.53	3.07	0.092	0.015	7.24	2.86	0.092	0.015
set10	7.53	3.07	0.095	0.016	7.24	2.86	0.095	0.015

The next task is to analyze the precision and noise characteristics of the circuit. For this, the standard deviation (sd) of the outputs recorded from the ten sets of the measurements were studied for both amp1 and amp2. In each set, the standard deviation in %sd=(sd/fsd)*100%, where fsd denotes the full scale division, is calculated for each input. The corresponding plots for both the amplifiers are shown in Fig. 3. These plots show that the values are of the order of 0.005V for both the amplifiers upto ±0.1V, beyond which the deviations increase with a limiting value of 0.013V at 300mV input. These results are in accordance with those obtained for the preliminary circuit [11]. From these studies, it may be inferred that both the circuits provide linear, repeatable outputs with minimal deviations over the expected range of input biosignals.

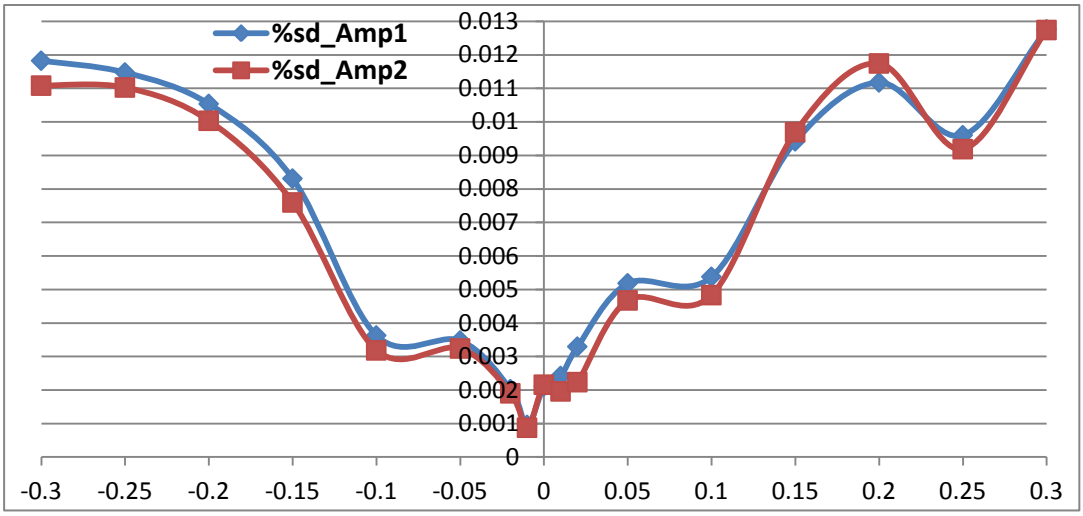

Figure 3. Std. deviation, in %, of amp1(blue) and amp2(red) for corres. input voltages, in V

IV. DYNAMIC CALIBRATION OF THE SYSTEM USING BIOPOTENTIALS

In the next stage of work, it is required to ascertain whether these circuits are capable of providing the required reliable signal conditioning for the measurement of actual human biopotentials. In order to do so, biopotentials, both direct and amplified, have been recorded simultaneously from both hands of various human subjects at various instants of time. Prior to data acquisition, the human subject was made to lie down on a bed placed in a cool, silent atmosphere, keeping both eyes closed. Thereafter, as in [2], the biopotentials have been acquired simultaneously using two pairs of Ag-AgCl electrodes from both the hands of the subject for the stipulated time span of 120s using the same system as detailed in Section III. For this, one electrode of a pair has been attached to the middle phalange of the index finger of one hand, while the other has been attached to a similar location of the middle finger of the same hand of the human subject. Since these pairs of electrodes provide the differential amplifier inputs, hence the effects of ground potentials as well as external noise sources are minimized.

a. Comparison of direct and amplified outputs

For the dynamic calibration of both the signal conditioning circuits, the biopotentials have been recorded directly from the electrodes as well as from the amplifier connected to it using the procedure stated above and a total of 20 such sets of readings have been recorded from each hand of some human subject. Four channels of multimeter readings have been recorded simultaneously

in the PC using two adapters, one for each hand. The biopotentials acquired directly from the pairs of electrodes on the left and right hands are recorded in Channel-1 as C1 and Channel-2 as C2 respectively. Amp1 is connected to the left pair of electrodes while amp2 is connected to the right pair of electrodes. The biopotentials acquired from amp1 (left) and amp2 (right) are recorded in Channel-3 as C3 and Channel-4 as C4 respectively.

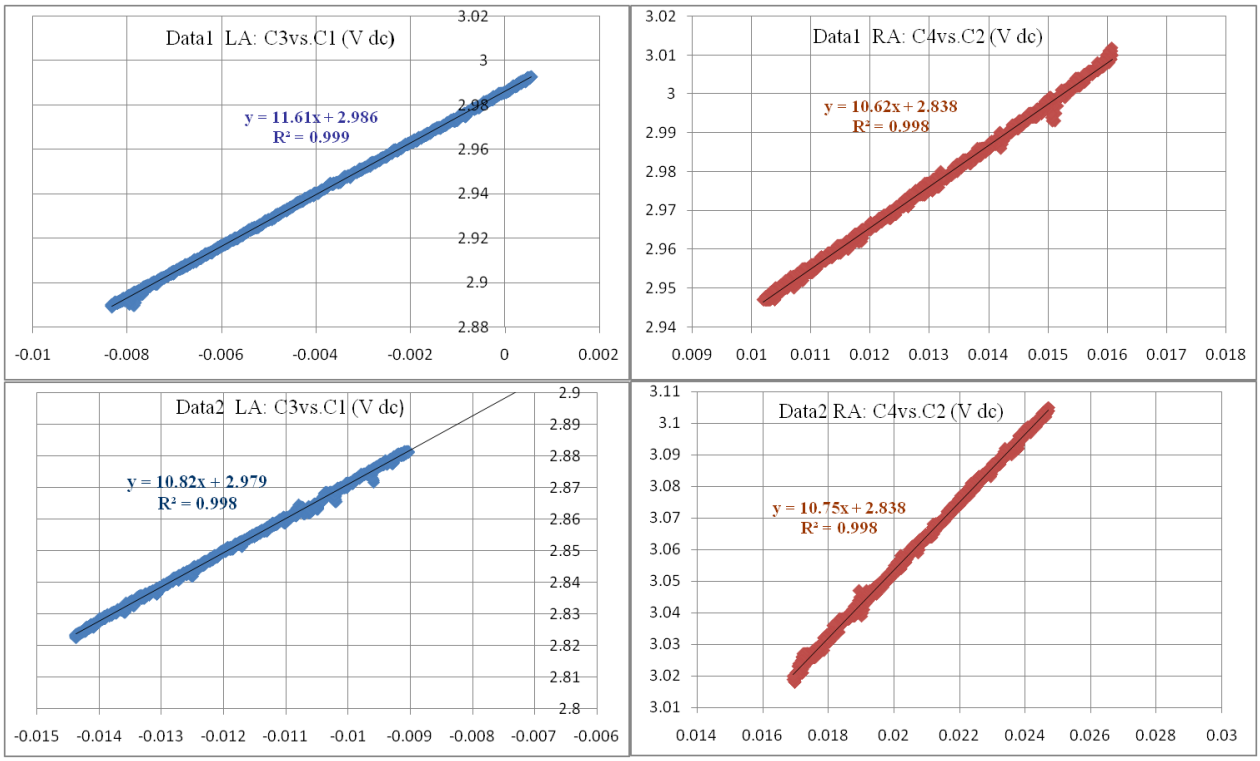

Figure 4. Amplified outputs, C3 and C4, in V, for the corresponding electrode outputs, C1 and C2, in V, for left (LA) and right hand (RA) respectively

Some typical plots of the amplified outputs of each hand vs, the electrode outputs of the same hand, specifically C3 vs. C1 for the left hand (LA) and C4 vs. C2 for the right hand (RA) are shown in Fig. 4. It is observed that the ranges of C1 and C2 vary in all these cases. This supports the observation in [2] that the voltage signal measured across the two fingers of each hand is time-varying and is different for each hand. As also expected, the voltage signals obtained directly from the electrodes, namely C1 and C2, are in the millivolt range while the corresponding amp1 and amp2 outputs, namely C3 and C4, are in the volt range. It is further observed from the plots that the overall natures of the recorded biopotentials are quite similar and show an overall linearity in their responses.

b. Analysis of acquired biopotentials

In order to analyze this further, the linear fit analysis was performed for all the 20 sets of recorded data for each hand and as in the case of static calibration, in this case too, the obtained values of the gain m and the bias c as well as the calculated values of their standard deviations s_m and s_c have been stated in Table 2.

Table 2: Gain and bias values, with their sd, for 20 sets of amplified outputs

	Amplifier 1				Amplifier 2			
	m	c (V)	s_m	s_c (V)	m	c (V)	s_m	s_c(V)
set1	11.61	2.99	4.47E-05	2.48E-07	11.28	2.78	2.66E-05	3.87E-07
set2	10.83	2.98	2.33E-05	2.74E-07	10.76	2.84	1.69E-05	3.49E-07
set3	11.10	2.99	5.15E-05	3.00E-07	10.62	2.84	2.17E-05	2.81E-07
set4	11.19	2.92	3.70E-05	2.89E-07	13.01	2.84	3.25E-05	3.27E-07
set5	17.58	2.91	4.69E-05	3.35E-07	11.67	2.86	1.21E-05	1.01E-07
set6	18.59	2.90	3.24E-05	2.63E-07	12.99	2.80	1.33E-04	4.82E-07
set7	14.37	2.94	5.68E-05	2.96E-07	9.94	2.73	3.37E-05	3.28E-07
set8	12.20	2.93	4.37E-05	2.77E-07	12.93	2.85	1.75E-05	1.23E-07
set9	15.58	2.92	5.78E-05	3.33E-07	9.45	2.85	4.96E-05	2.44E-07
set10	24.38	3.07	2.18E-05	2.53E-07	10.61	2.77	7.54E-05	1.51E-07
set11	14.44	2.93	9.13E-05	4.68E-07	9.70	2.85	3.95E-05	3.20E-07
set12	8.88	3.01	5.58E-05	5.20E-07	14.31	2.84	1.75E-05	1.05E-07
set13	11.06	2.93	7.16E-05	2.98E-07	17.20	2.85	1.48E-04	3.45E-07
set14	5.86	2.89	2.94E-04	5.97E-06	9.27	2.82	6.27E-05	5.63E-07
set15	12.56	2.88	1.07E-04	3.63E-07	9.04	2.77	1.53E-02	6.09E-06
set16	3.40	2.84	7.49E-05	2.37E-06	9.88	2.85	1.11E-04	2.80E-07
set17	15.30	2.97	3.83E-05	4.73E-07	11.90	2.81	1.86E-05	4.91E-07
set18	13.74	2.92	2.92E-04	5.42E-07	16.4	2.82	1.13E-03	4.39E-07
set19	14.25	2.86	1.04E-04	1.06E-06	12.43	2.82	7.00E-05	1.30E-07
set20	13.32	2.92	1.63E-04	4.35E-07	12.38	2.76	1.70E-04	5.89E-07

As is to be expected, in these cases, the variations in gain as well as bias are much larger than those observed in the static calibration results. The cumulative distribution function (cdf) plots of the gain and the bias voltages of amp1 and amp2 have been shown in Fig.5 to depict the variations in these two parameters for both the circuit outputs. However, both s_m and s_c for both amp1 and amp2 outputs are significantly lower than the corresponding static calibration values. This can be ascribed to the fact that the actual biopotentials for all 20 sets of data are limited

within the range (-12.36)mV to 31.17mV for the left hand and within the range 9.66mV to 26.44mV for the right hand. Hence, as observed in the static calibrations also, the standard deviations in the working range in each case are much lower than the worst case values, thus ensuring higher reliability than that expected from the static calibration results. An analysis of the gains shows that the average gain for amp1 is 13.00 with the mode value of 11.24 while for amp2, the corresponding values are 11.80 and 9.55. It is seen that both these values are significantly larger than the respective static calibration gains but in both cases, the average gains for amp1 are larger than those for amp2, thus maintaining parity. The average bias voltages for amp1 and amp2, specifically 2.93V and 2.82V, are closer to the corresponding static calibration values of 3.07V and 2.86V respectively.

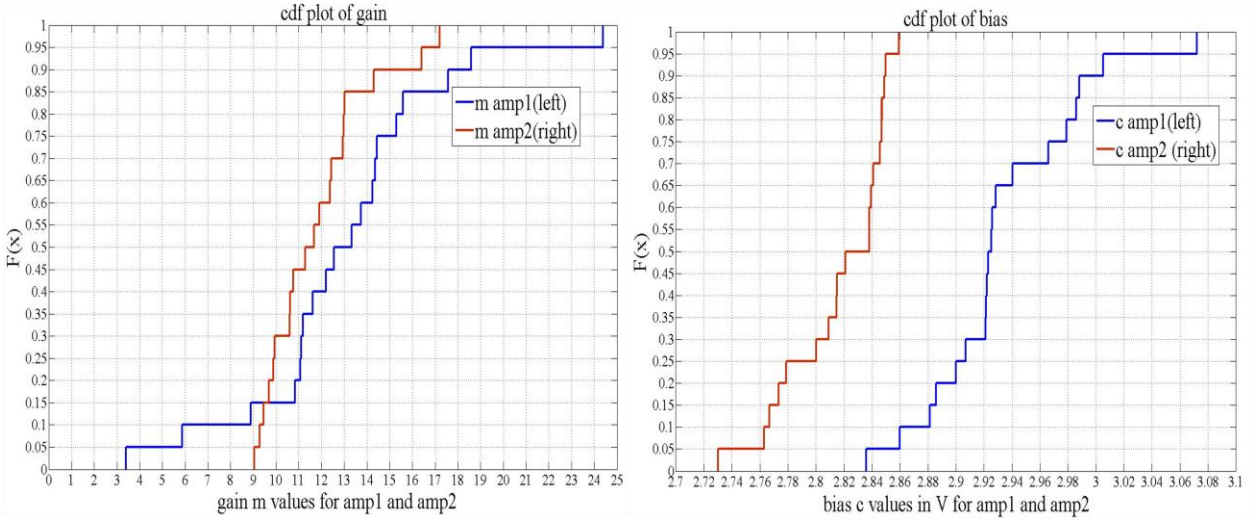

Figure 5. Cdf plots of gain m and bias c for amp1 (left) (blue) and amp2 (right) (red)

IV. ANALYSIS OF THE ACQUIRED BIOPOTENTIALS

In order to analyze the consistency of the outputs from the signal conditioning circuit, the electrode outputs, C1 and C2, as well as the corresponding amp1 and amp2 outputs, C3 and C4 respectively, for all the 20 sets of recorded data for each hand have been depicted as a line plot in Fig. 6. AVG LD and AVG RD indicate the line plots for the electrode outputs of the left and right hands of the human subjects, AVG LA and AVG RA indicate the amp1 and amp2 outputs respectively while AVG LA TH and AVG RA TH indicate the theoretically obtained amplifier outputs calculated using the respective static calibration gain and bias values of 7.55 and +3.07V for LA; and 7.25 and +2.86V for RA.

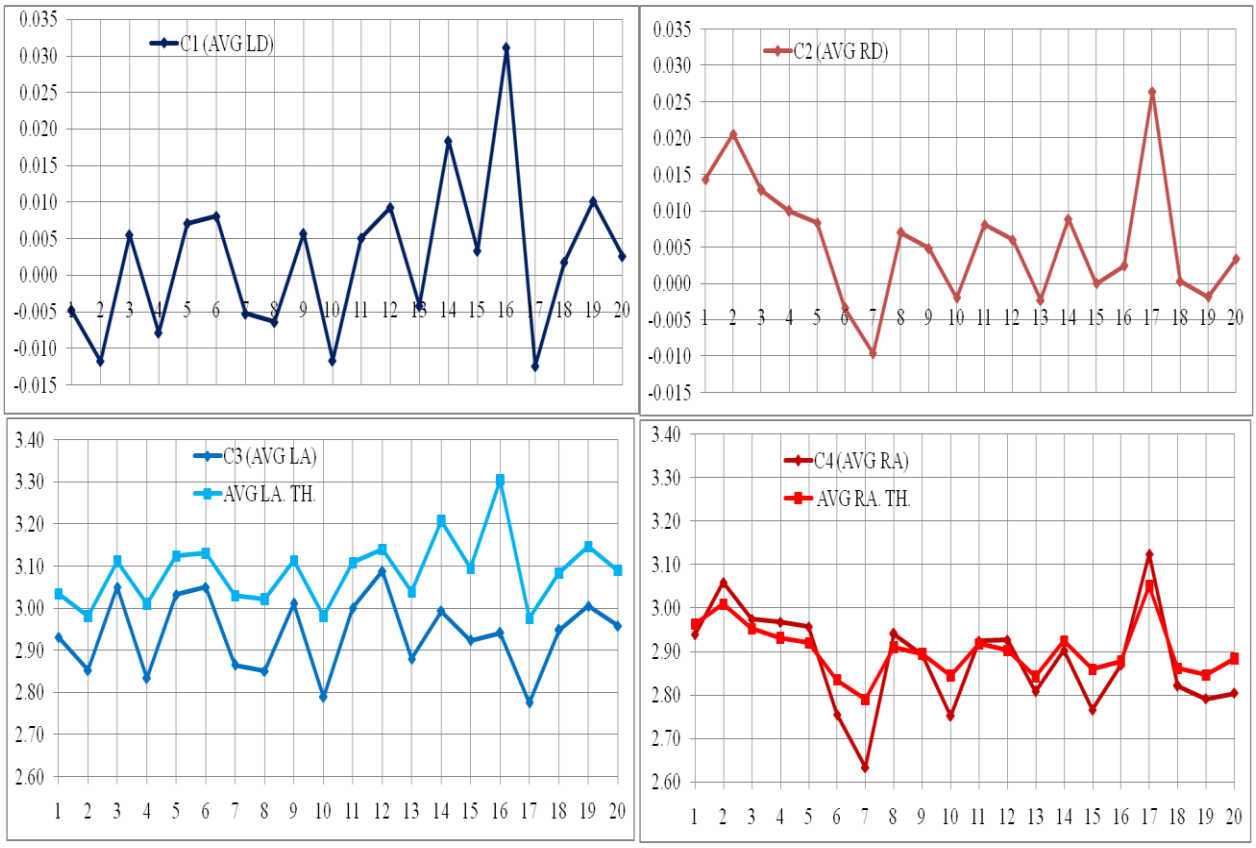

Figure 6. Average biopotentials, in V, obtained from left and right hand of a human subject. Electrode outputs: AVG LD and AVG RD; Amplified outputs: AVG LA and AVG RA with their theoretical values: AVG LA TH and AVG RA TH.

From Fig. 6, it is observed that the average output values obtained using the instrumentation system are more or less in correspondence with those obtained directly from the electrode output. Comparing the AVG LA and AVG LA TH patterns, as well as the AVG RA and AVG RA TH patterns, it is observed that the biopotentials acquired from the instrumentation system are slightly different from the theoretically expected values. The average errors are obtained as 4.77% and 0.74% for the data recorded from the left hand and right hand respectively, which are both within 5% limits and this indicates a good reliability of the data recorded using the signal conditioning circuits.

The next task undertaken is to analyze the normality of the recorded signals. For this purpose, the cumulative distribution functions (cdf) of the average outputs for both hands have been plotted in Figure 7 for the direct and the amplifier outputs respectively. It is observed from the plots that the

average values of the measured dc voltages from the left hand (LD) vary within -12.36mV to 31.17mV with a mean value of 2.2mV, while 1σ (68.27%) of the data lie between -12.26mV to 7.14mV. The average voltages recorded from the right hand (RD) vary within -9.66mV to 26.44mV, its mean value is 5.71mV and 1σ (68.27%) of the data lie between -2.62mV to 9.90mV. The corresponding analysis of the amplifier outputs show that the average values of the amplified dc voltages from the left hand (LA) vary from 2.75V to 3.19V and those from the right hand (RA) vary from 2.63V to 3.12V. It is also observed that the mean value for LA is 2.93V and 1σ (68.27%) of the data lie between 2.78V to 3.08V. The mean value for RA is 2.84V and 1σ (68.27%) of the data lie between 2.77V to 2.97V.

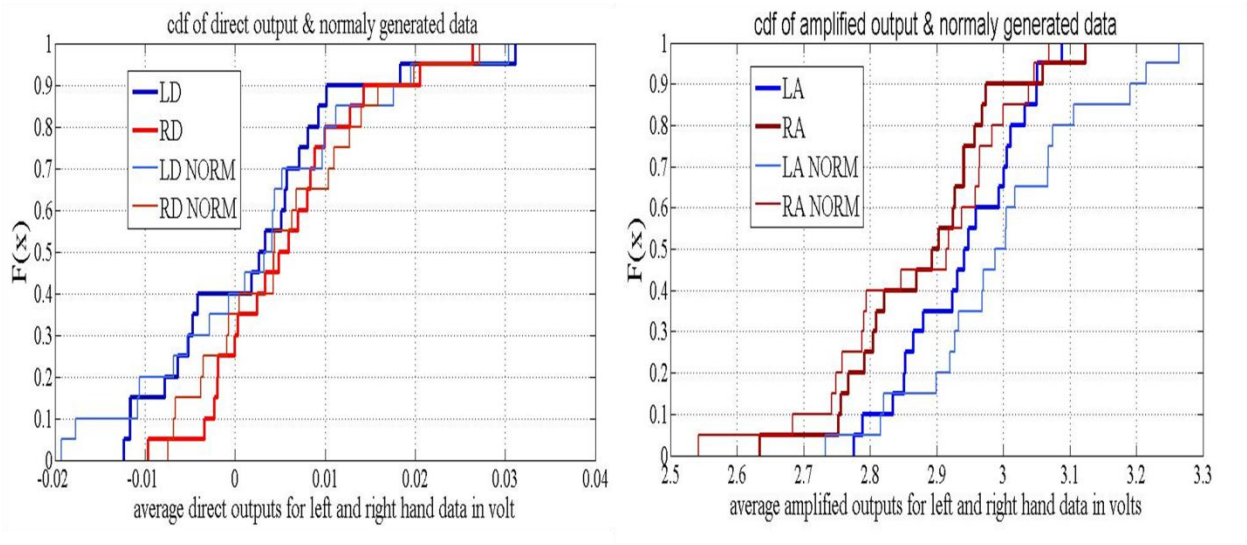

Figure 7. Cdf plots of average of electrode outputs LD and RD and amplified outputs LA and RA for left and right hand respectively along with their corresponding normal cdf plots

Cdf plots of theoretically generated sets of normally distributed data using the aforementioned mean and standard deviations have also been plotted for LD, RD, LA and RA in Fig. 7. These provide a comparison of the distributions in terms of their closeness to the typical normal distribution. The corresponding values of kurtosis have been calculated to be 3.73 for LD, 1.98 for LA, 3.26 for RD and 2.87 for RA. It is known that a value of 3 for kurtosis indicates a normal distribution, while values less than 3 indicate that the data are less outlier prone than a normal distribution and values greater than 3 indicate that the data are more prone to outliers. Both from the cdf plots and the kurtosis values, it is thus observed that while the electrode outputs LD and RD are more outlier prone than their normally distributed values, the corresponding amplifier

outputs LA and RA are less outlier prone. Hence, the data from LA and RA are found to be more reliable in this sense than the corresponding LD and RD values.

Thus in view of all these observations, it can be inferred that the developed signal conditioning circuits fulfill the objectives of providing reliable amplified outputs for the biopotentials without added distortions in the signal and hence may be used to facilitate future analysis of the acquired human biopotentials.

V. CONCLUSIONS

In the present work, the development, calibration and testing of two identical signal conditioning circuits, that can be used to enhance the signal level of the biopotentials measured using a non-invasive scheme[2] for the condition monitoring of the health of the human system, has been presented. The objective of using the circuits is to measure the human biopotentials simultaneously from both hands and then to enhance the signals reliably to a higher level in order to obtain higher resolution but with minimal signal modulation.

Each circuit is designed to amplify and add a suitable bias of +3V to the input voltages such that inputs within [-300mV, +300mV] are amplified and scaled to [+1V, +5V]. A pair of electrodes along with each of the circuits, that are henceforth referred to compositely as amp1 and amp2, was first calibrated with fixed dc inputs spanning the specified range, and 10 such sets of readings were recorded for each circuit. An analysis of the data shows that both amp1 and amp2 provide linear and repeatable measurements for the whole input range, with acceptable and similar values of standard deviations. For a straight line fit, obtained using the least squares method [10], the average gain and bias value for amp1 is observed to be 7.55±0.27 and 3.07±0.04V, while for amp 2, the corresponding values are 7.25±0.27 and 2.86±0.04V, as compared to the design gain and bias values of 6.7 and +3V, with a goodness of fit factor of 0.997 in both the cases. The standard deviations of the gain and bias voltages have also been calculated and these have been found to be of the order of 0.005V for both the amplifiers upto ±0.1V, beyond which the deviations increase with a limiting value of 0.013V for a 300mV input. From these studies, it may be inferred that both the circuits provide linear, repeatable outputs with minimal deviations over the expected range of input biosignals.

In the next stage of work, it is required to ascertain whether these circuits are capable of providing the required reliable signal conditioning for the measurement of actual human biopotentials. In order to do so, biopotentials, both direct and amplified, have been recorded

simultaneously from both hands of various human subjects at various instants of time. These biopotentials have been recorded directly from the electrodes as well as from the amplifier connected to it and a total of 20 sets of readings have been recorded from each hand of the human subjects. Thus, four channels of multimeter readings; two directly from the pairs of electrodes on each hand and one each from amp1 and amp2 outputs, have been recorded simultaneously for each set of readings. A comparison of the amplified outputs of each hand vs, the electrode outputs of the same hand shows that the overall natures of the recorded biopotentials are quite similar and show an overall linearity in their responses.

From the linear fit analysis of these dynamic biopotentials, it is observed that the variations in gain as well as bias are much larger than those observed in the static calibration results, as is to be expected. However, the standard deviations of the gain and the bias voltages for both amp1 and amp2 outputs are significantly lower than the corresponding static calibration values. This can be ascribed to the fact that the actual biopotentials for all 20 sets of data are limited within the range (-12.36)mV to 31.17mV for the left hand and within the range 9.66mV to 26.44mV for the right hand. Hence, as observed in the static calibrations also, the standard deviations in the working range in each case are much lower than the worst case values, thus ensuring higher reliability than that expected from the static calibration results. An analysis of the gains shows that the average gain for amp1 is 13.00 with the mode value of 11.24 while for amp2, the corresponding values are 11.80 and 9.55. It is seen that both these values are significantly larger than the respective static calibration gains but in both cases, the average gains for amp1 are larger than those for amp2, thus maintaining parity. The average bias voltages for amp1 and amp2, specifically 2.93V and 2.82V, are closer to the corresponding static calibration values of 3.07V and 2.86V respectively. Using these dynamic gain and bias values for both the amplifiers, the theoretical value of the average amp1 and amp2 outputs were calculated and compared with the practically obtained averages. The errors are obtained as 4.77% and 0.74% for the data recorded from the left hand and right hand respectively, which are both within 5% limits and this indicates a good reliability of the data recorded using the signal conditioning circuits.

Thereafter, the cumulative distribution functions (cdf) of the average outputs for both hands have been plotted for the direct and the signal conditioning circuit outputs and compared with the respective standard normal cdf plot for the same values of mean and standard deviations. Close correspondences of the respective plots validate the normality of the data recorded. Thereafter, the

kurtosis values have been calculated for the left (L) and (R) hand data for both the direct (D) and the amplified (A) outputs to be 3.73 for LD, 1.98 for LA, 3.26 for RD and 2.87 for RA. From the plots and the kurtosis values, it is observed that LD and RD is more outlier prone than their normally distributed values and LA and RA are less outlier prone. Hence, in this sense, the data recorded using the signal conditioning circuits are found to be more reliable than the corresponding directly measured biopotentials.

Thus, the signal conditioning circuits developed, calibrated and tested in the present work provides a linear amplification, as well as suitable bias, of the directly recorded biopotentials within allowable errors and with improved reliability.

In the future scope of work, the dynamic characteristics of this circuit has to be studied in more detail. A detailed study of the frequency response of the instrumentation system has to be undertaken. Proper isolation circuits also have to be incorporated for patient safety. Thereafter, similar calibration procedures and analysis of the modified circuits have to be undertaken to standardize the circuit and also to validate its dynamic performance. On the other hand, the developed signal conditioning circuit can be used to acquire the biopotentials of a larger corpus of human subjects over longer periods of time. The data acquired from these subjects then have to be analyzed with the objective of inferring the health condition of the subjects in comparison with data obtained from standard available medical practices.

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