Continuous Impedance, Force, and Acceleration Monitoring for Motion Artefact Reduction in EEG

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Abstract

Electroencephalograph (EEG) is used in various applications such as diagnosing patients suffering from epilepsy or seizures. Motion artefact is the noise recorded together with the desired biopotential signals. It is mainly introduced by the relative motion between the measurement electrode and the human scalp. Dry electrodes are preferred in long term monitoring because gel is not required, although dry electrodes are more vulnerable to motion artefact. The frequency range of motion artefact overlaps with the frequency range of the EEG. Thus it is difficult to deduct motion artefacts from recorded signals. In imec, a low power wireless headset has been developed for long term EEG acquisition. Since motion artefact introduces significant signal distortion, finding a suitable signal that can help in locating these artefacts is of utmost importance. In order to find the most appropriate signal for the motion artefact detection and possibly also prediction and removal, the relation between EEG, impedance, force and acceleration were investigated. We analysed the influences of external forces, head movements and daily activities on the EEG and electrode-skin impedance magnitude. 11 subjects participated the experiment. Cross correlation coefficient analysis was done to indicate the linear correlations between EEG and impedance, EEG and force, EEG and acceleration, impedance and force, and impedance and acceleration. The results demonstrate that the EEG, the impedance and the force are highly correlated when only external force is applied on the electrodes. However, when body movements are involved the cross correlation is lower due to the non-linearity of the signals. Both positive and negative correlation could be observed between the impedance and the EEG. The relation between the impedance and the EEG varies across the people and due to the motion. In conclusion, impedance is the best candidate for motion artefact detection in EEG compared with force and acceleration.

I. Introduction

Brain activities result in the changes in the electrical potential on the surface of the scalp. The electrical potential can be recorded by the electroencephalograph (EEG) systems from various locations on human scalp [1, 2]. The characteristics of are highly dependent on the degree of activity of the cerebral cortex. In general, the EEG has amplitude from 1 up to $100\mu V$ with frequencies of 0.5 to $100Hz$. Some pathological disorders such as epilepsy induce large electrical discharges that results in EEG amplitudes up to $1mV$ [2, 3]. EEG is used as a diagnostic technique, for example, for patients suffering from epilepsy or seizures [4], and in sleep monitoring (polysomnography). Due to the temporal resolution, ease of operation, and low cost, EEG is used to provide an alternative way of communication and control by merely using brain activity. This is also called brain computer interface (BCI).

In some of the EEG applications, long term EEG monitoring is required to provide sufficient information. One example is handling patients suffering from epilepsy. Going in this direction, a number of low power wireless headsets for long term EEG acquisition have been developed. Currently, these solutions are aimed at daily life usage. The Emotiv EPOC [5] provides access to 12 hours continuous EEG monitoring with a set of 14 electrodes plus 2 references. Neurosky Mindset [6] uses one dry contact resistive electrode to measure EEG at F_{P1} position (according to the International 10-20 system) to detect multiple mental states of the user simultaneously. The imec wireless low-power active electrodes EEG headset [7] can continuously record 8-channel EEG signals with dry electrodes.

Dry electrodes are commonly selected in long term monitoring in EEG mainly because they do not acquire gel. Therefore, drying out of gel during the acquisition is no more a concern. Skin irritation caused by conductive gel can also be avoided. Nevertheless dry electrodes are more sensitive to noise. Since gel provides a better adhesion, dry electrode is more vulnerable to motion artefact.

Motion artefact is the noise recorded together with the desired biopotential signals. It is mainly introduced by relative motion between the measurement electrode and the human scalp. The relative motion introduces disturbances of the electrical charge at the electrode-electrolyte interface. It also changes the impedance of epidermis layers of the skin, which is resulted from the skin deformation caused by the relative motion. By applying non-polarizable electrodes, motion artefacts introduced by the disturbances of the charge can be minimized. When a proper electrode has been selected, the motion artefact is mainly caused by the deformation of skin around the electrode[8].

Most of the motion artefacts concentrate within the frequency range between 0.1 Hz and 30 Hz, which falls within the frequency range of EEG. The dynamic range of motion artefact in bioprotential signals could have several millivolts . Motion artefacts can contaminate the recorded biopotential signals. They make extracting valuable information more difficult.

Since motion artefact has influences on the electrode-skin impedance, Ottenbacher *et. al* proposed a method to detect motion artefact in Electrocardiogram (ECG) by simultaneously measuring impedance and ECG [9]. They have proved that the motion artefact detected in the impedance can be used in artefact detection algorithm in ECG. The quality of the ECG signal can be improved by the algorithm. Because of the differences in the skin structures and the signal properties, further investigation is required to understand whether impedance is also suitable to be used in motion artefact detection algorithm in EEG.

Essentially, relative motion between skin and electrode is generated by the force changes on the electrode. Acceleration can be detected wherever motion occurs. Thus, in our study, in addition to impedance, force and acceleration were also investigated.

The goal of this project is to understand the relation between the EEG, the impedance, the force and the acceleration, in order to evaluate how these signals could be used in motion artefact recognition and removal.

II. Methods

II.1 Setup

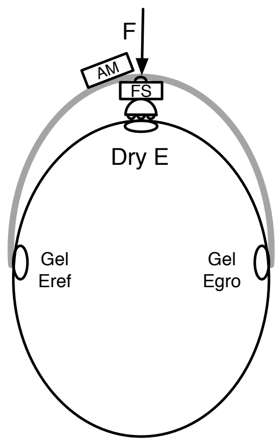


Figure 1: *The schema of the headset. The dry electrode, the force sensor and the accelerometer were mounted on the headset. The ground electrode and the reference electrode were attached symmetrically on the mastoid processes. E: measurement electrode; E_{ref}: reference electrode; E_{gro}: ground electrode; FS: force sensor; AM: accelerometer; F: force.*

The measurement setup consists of the following components:

- 8-channel *EEGv2.0* system (imec)
- NI USB-6229 Multifunction DAQ (National Instruments)
- 1 piezo-disk force sensor
- 1 WGA-670B instrumentation amplifier (Kyowa)
- 1 ADXL335 triple-axis accelerometer (Adafruit)
- 1 EL120 Ag/AgCl dry electrode (Biopac)
- 2 Ag/AgCl cup wet electrode
- 1 rigid headset

Figure 1 illustrates the configuration of the headset. The dry electrode, the force sensor and the accelerometer were mounted on the headset. The force sensor was positioned above the measurement electrode. This was done to assure the force measured by the force sensor was equivalent to the force component perpendicularly applied to the electrode. The accelerometer was fastened on top of the headset. The 2 wet electrodes (ground and reference) were attached symmetrically on the mastoid processes by conductive gel and medical adhesive tape. The ground here is referred as patient ground. The reason that the 2 wet electrodes were selected as the ground electrode and the reference electrode was because gel could provide a better contact between the skin and the electrode. In such case, the motion artefacts were mainly generated by the movements of the dry (measurement) electrode.

The headset was connected into the 8-channel $EEGv2.0$ system [10] developed by imec (Figure 2). Only 2 channels were used in the experiment. Channel 1 was connected with the headset to measure the EEG and the impedance. Channel 2 was connected to a $33k\Omega$ resistor to inspect if the system was functioning properly.

The EEG signal represents the measured potential difference between the measurement electrode and the reference electrode. The signal was buffered by amplifiers with G = 1, followed by 100 times amplification (G = 100). The EEG was digitized using a 12-bit ADC converter having voltage range of $1.66V$ with the midline at $0.9V$. The EEG (in volts) could be calculated using the following formula:

$$EEG = \frac{1}{100} \times (1.662 \times \frac{V_{out}^{EEG}}{2^{12}} - 0.9) \qquad (1)$$

where V_{out}^{EEG} is the digitized EEG value after ADC.

Due to an uneven distribution of anions and cations, a half-cell potential can develop across the skin-electrode interface. Using silver/silver chloride (Ag/AgCl) nonpolarized electrodes dramatically reduces the half-cell potential to approximately $220mV$. This voltage appears as a dc offset in the biopotential signal. In the case of an EEG measurement, the magnitude of EEG is from 1 upto $100\mu V$. The considerably high dc offset would exceed dynamic range of the system after amplification. This would affect the functionality of the

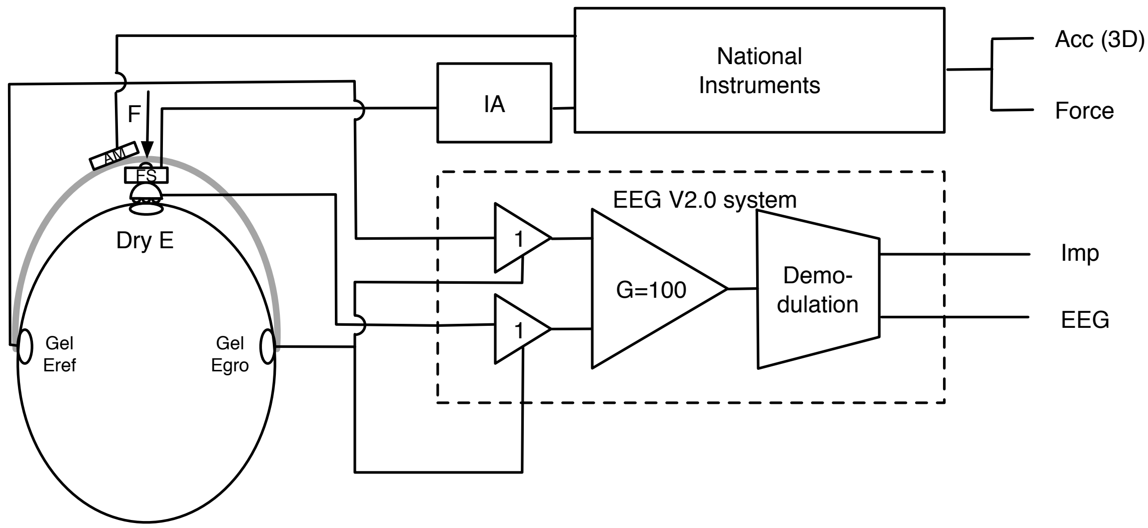


Figure 2: *The schema of the measurement setup. IA: instrumentation amplifier; E: measurement electrode; E_{ref}: reference electrode; E_{gro}: ground electrode; FS: force sensor; AM: accelerometer; F: force.*

system. Furthermore, because the amplifier is used prior to A/D conversion, after the amplification the noise introduced by the dc offset can be an important contributing factor towards the overall signal-to-noise ratio. Thus a first order high-pass filter with a cut-off frequency of $0.4Hz$ is applied in the 8-channel $EEGv2.0$ system to filter out the dc offset voltage before the signal being amplified.

The $EEGv2.0$ system includes current generation modules for each electrode for the impedance measurement. $50nA$ square wave current peaks at the frequency of $1kHz$ were injected during the experiment. After the buffer (G = 1) and amplification (G = 100), the signal was demodulated. Because of the low-pass filtering in the demodulation step of the $1kHz$ signal, only the first harmonic of the square wave was amplified, leading to an effective gain of the transfer function of 81. The impedance magnitude of the electrode-skin interface was measured by demodulating in-phase component (Z_i) and quadratic component (Z_q) of the impedance. Each component was digitized. The impedance magnitude (in ohms) can be estimated using Z_i and Z_q by the formula:

$$\mid Z_i \mid = \frac{1}{81 \times I_d} \times \sqrt{(1.662 \times \frac{V_{out}^i}{2^{12}} - 0.9)^2}$$

$$\mid Z_q \mid = \frac{1}{81 \times I_d} \times \sqrt{(1.662 \times \frac{V_{out}^q}{2^{12}} - 0.9)^2}$$

$$\mid Z \mid = \sqrt{Z_i^2 + Z_q^2} \tag{2}$$

Where V_{out}^i is the in-phase (real) voltage and V_{out}^q is the quadratic (imaginary) voltage.

The force and the acceleration were recorded by the $NIUSB - 6229DAQ$ developed by National Instruments (Figure 2). Before entering the $NIUSB - 6229DAQ$, the force was transformed into voltage and displayed by the instrumentation amplifier. The impedance, the force and the acceleration were displayed simultaneously in real-time in a custom-made Matlab graphical user interface (Mathworks, USA). The experimenter controlled the recording time of the 2 systems in the interface.

One limitation of the measurement setup is that due to the data acquisition protocols, the signals collected by the $EEGv2.0$ system and the $NIUSB - 6229DAQ$ could not be perfectly aligned in time.

II.2 Subjects

11 subjects (from 22 to 36 years old; 8 men) participated the experiment. The protocol was explained before the experiment and subjects signed the informed consent prior to the experiment.

II.3 Experimental protocol

The subjects were asked to sit in a comfortable chair with the measurement headset fixed on the head. The quality of the signals was ensured by the experimenter through visual inspection. When it was necessary, the experimenter had to readjust the headset. After subjects put the headset on, 60s was given to the system to stabilise. During the 60s external force and movement were tried to avoid. Every recording started with 30s where the subject stayed steady without any external force or movement.

The dry electrode was positioned approximately at C_z position (according to the International 10-20 system). The quality of the impedance signal was controlled by visual inspection and probing the response to different forces. The experiment consisted of three main sessions:

- external force
- head movement
- daily activities

To assure that the system was functioning properly, the impedance measured at Channel 2 was monitored. When it was around 33k, it was assumed that the system was working properly.

The EEG, impedance, force and acceleration were recorded at a sampling rate of 1024Hz. The EEG, the impedance, the force and the acceleration of 11 subjects in 8 different tests were collected during the experiment.

II.3.1 External force

In the external force session, force was generated manually by the experimenter. This introduced variations in the magnitude of the force. The force was rendered by pressing the headset perpendicularly to the scalp with a firm object at C_z position. The magnitudes of three types of force were studied.

Continuous force: Three constant forces, each with period of 60s applied on the electrode were interspersed with 60s of no force application. The magnitudes of the forces were kept at around 1.5, 2.5 and 4N in each of the 60s segments.

Repetitive force: Three repetitive forces (block-shaped) each with a period of 60s were applied on the electrode. The forces were interspersed with 60s of no force application. The periods of the forces were at around 3, 5, and 10s in each of the 60s segments. The force magnitude was kept around 2.5N.

Impactive force: A period of 180s was recorded where one punch force was applied approximately every 5s. The peaks in the applied force were within the range from 1N to 5N.

II.3.2 Head movement

In the head movement session, the subject was asked to sit in a chair and try to avoid other movements during the experiment. Two types of head movements were investigated.

Nodding: The subject was asked to nod within 2s with angular magnitude not bigger than 45 degrees, followed by 2s of no head movement. In total, 10 nodding movements were recorded.

Tilting: The subject first tilted his/her head to the right, then to the left, and back to the upright position. The subject was asked to keep the head movement in the coronal plane with angular magnitude smaller than 60 degrees. The duration of this movement was about 5s, followed by 5s of no head movement. In total, 10 tilting movements were recorded.

II.3.3 Daily activity

In the daily activity session, the subjects were asked to perform daily activities with minimized relative head movements (relative to the trunk). Three types of daily activities were included.

Standing up: The subject was asked to stand up while keeping neck in the upright position to minimize head movement. Every standing up was followed by $5s$ standing straight. Then the subject was asked to sit down with neck staying in the upright position, followed by $5s$ sitting in the initial position. In total, 10 standing up movements and 10 sitting down movements were recorded.

Walking on the spot: The subject was asked to walk on the spot while keeping neck in the upright position to minimize head movement. Such walking activities were done at a low, normal, and fast pace within three $60s$ segments. They were interspersed with $30s$ standing straight where no movement was involved. In total, 3 walking activities with 3 different paces were recorded.

Jumping on the spot: The subject was asked to jump on the spot while keeping neck in the upright position to minimize head movement. Every jumping was followed by $5s$ standing straight where no movement was involved. In total, 10 jumping movements were recorded.

III. Data analysis

III.1 Cross correlation coefficient analysis

The cross correlation of mean-removed sequences can be estimated as:

$$\Phi_{xy}(m) = \frac{\mathbf{E}\{(x_{n+m} - \mu_x)(y_n - \mu_y)\}}{\sigma_x \sigma_y} \tag{3}$$

where μ_x and μ_y are the mean values of the two stationary random processes, σ_x and σ_y are the standard deviation, and $\boldsymbol{E}$ is the expected value operator.

The cross correlation coefficient demonstrates the similarity of two signals as a function of a time lag applied to one of them. A correlation coefficient value of +1 means there is a perfect positive linear relationship where the two signals are in-phase. -1 means there is a perfect negative linear relationship where the two signals are in antiphase. The value between -1 and +1 indicates the degree of linear dependency between the signals. An absolute value of coefficient that is higher than 0.6 is regarded as a strong correlation between the two signals. As it approaches zero there is less of a relationship. 0 means the two signals are not correlated. The time lag when the maximal cross correlation coefficient is reached indicates the delay between the two signals. Unfortunately, in our recording the data collected by the two systems could not be perfectly aligned in time. Thus the lag cannot demonstrate the delay between two signals. It shows the combination of the delay between the signals and the delay between the two systems. This is not considered as valuable information. Therefore, the time lag is not included in the analysis.

The shape of the cross correlation also provides information about the two signals. When the two signals contain similar trends, the cross correlation values exhibit slow decay as the time lag increases. When the data contains a periodic component, the cross correlation will show similar periodic behaviour at the similar frequency. If cross correlation contains an oscillation at the same frequency, seasonal fluctuations exist between the 2 signals. The 2 signals are short-term correlated when the cross correlation is characterized by a fairly large value followed by 2 or 3 more coefficients that get successively smaller, and the cross correlation gets to 0 for larger time lag. If one signal tend to alternate on different sides of the overall mean, the cross correlation would also tend to oscillate.

One impediment of the high-pass filter in the $EEGv2.0$ system is that it distorted EEG signals, which might influence the results of the data analysis. Hence, in the cross correlation coefficient analysis we applied the same high-pass filter (first order; $0.4Hz$ cut-off frequency) to the impedance, the force and the acceleration. Because the high-pass filter only affected the EEG signal, it was only applied when the correlation was calculated with the EEG (impedance-EEG, force-EEG and acceleration-EEG). In the impedance-force and impedance-force correlation analysis we used the unfiltered raw data.

III.2 Data selection

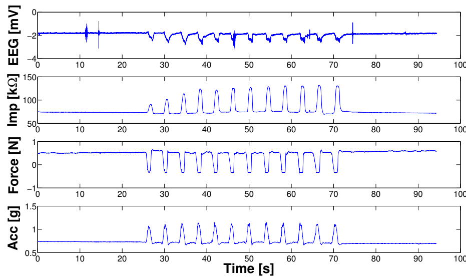


Figure 3: *The EEG, and the unfiltered impedance, force and acceleration in the nodding experiment of subject 11.*

The measurement of the nodding experiment of subject 11 is presented in Figure 3. The results illustrate that nodding movement caused associated responses in the EEG, the impedance, the force and the acceleration. Such clearly correlated changes were also observed in other experiments across subjects. This phenomenon demonstrated that these signals could be highly correlated. The fluctuations in the EEG, the impedance, the force and the acceleration had similar morphologies. Thus cross correlation coefficient was selected for the data analysis, which indicated the linear similarities between two signals. In total, 5 linear correlations were reported as follows:

- EEG and impedance (filtered)
- EEG and force (filtered)
- EEG and acceleration (filtered)
- impedance (unfiltered) and force (unfiltered)
- impedance (unfiltered) and acceleration (unfiltered)

When applied the whole data for cross correlation, noise decreased the coefficient values. Since the recorded signals contained a number of artefacts not introduced by force or movements, we selected segments containing only transitions caused by force or motion for correlation analysis. Segments had obvious data loss were excluded.

III.2.1 External force

For the continuous force experiment the purpose is to understand the impacts of the magnitude of the applied force on the EEG and the impedance. Thus the transition segments where force application and release occurred were selected (Figure 6). Those segments were chosen as $5s$ before and $5s$ after the force changes. The window length was $10s$.

For the repetitive force experiment, the intention was to investigate the influences of the period of the repetitive force on the EEG and the impedance. The segments were selected with respect to the period of force application ($3s$, $5s$, and $10s$).

For the impactive force, in order to comprehend the affects of the sharp force changes, 6 individual impacts were picked from the recorded data for every subject. At least one of the highest impactive forces and one of the lowest impactive forces were included. The selected segments were controlled so that they were evenly distributed in the complete data. The segments consisted of $3s$ before and $3s$ after the impacts. The window length was $6s$.

III.2.2 Head movement

In the nodding experiments, 6 out of 10 movements were chosen randomly for every subject in each test. Every segment included one complete nodding movement. $2s$ before and $2s$ after the midpoint of the acceleration changes were selected. The window length of the segments was $4s$. At least one movement in the beginning of the experiment and one movement in the end of the experiment were included. The selected segments were controlled so that they were evenly distributed in the complete data.

In the tilting experiments, 6 out of 10 movements were chosen randomly for every subject in each test. Every segment included one complete tilting movement. In the tilting test, $4s$ before and $4s$ after the midpoint of the acceleration changes were selected. The window length of the segments was $8s$. At least one movement in the beginning of the experiment and one movement in the end of the experiment were included. The selected segments were controlled so that they were evenly distributed in the complete data.

III.2.3 Daily activity

In the standing up experiment, 6 out of 10 segments including standing up and 6 segments including sitting down were selected randomly for every subject. 2.5s before and 2.5s after the mid point of the acceleration changes were selected. The window length of the segments was 5s. At least one movement in the beginning of the experiment and one movement in the end of the experiment were included. The selected segments were controlled so that they were evenly distributed in the complete data.

In the walking experiment, the intention was to understand if the walking frequency influences the EEG and the impedance. The segments were selected with respect to the walking speed (slow, medium and fast) in every subject.

In the jumping experiment, 6 out of 10 segments were chosen randomly in every subject were used for data analysis. Every segment included one complete jumping movement. 1.5s before and 1.5s after the mid point of the acceleration changes were selected. The window length of the segments was 3s. At least one movement in the beginning of the experiment and one movement in the end of the experiment were included. The selected segments were controlled so that they were evenly distributed in the complete data.

IV. Results

IV.1 Meta-analysis

IV.1.1 Cross experiment analysis

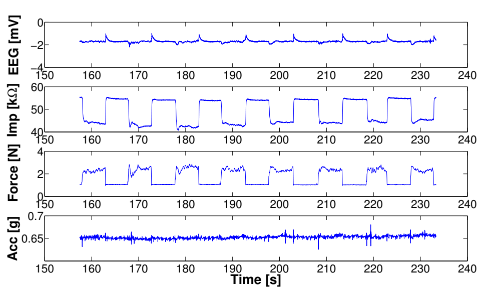
Table 1 demonstrated the means, peak-to-peak values and the standard deviations of the EEG, the impedance, the force and the acceleration in all the experiments. The mean EEG values were constant at around -1.7mV in most of the experiments except in the walking (-1.6mV) and the jumping (-1.4mV). The peak-to-peak values were extremely high in the walking and the jumping experiment (more than 3 times higher compared with the others). The highest standard deviation was achieved in the standing experiment followed by jumping and walking. In general, daily activities and rapid force changes introduced more variations in the magnitude of EEG. The mean impedance values were within the range from 20$k\Omega$ to 80$k\Omega$. There were obvious differences among the subjects and the different experiment sessions. Experiments that included body movements had higher mean impedance values than force application experiments. The most evident variation occurred in the jumping experiment, with a peak-to-peak value of 94$k\Omega$. The peak-to-peak values were lower in the repet-

Table 1: *The properties of the EEG, the impedance, the force and the acceleration across experiments. mean: mean value; max-min: peak-to-peak value; stdev: standard deviation.*

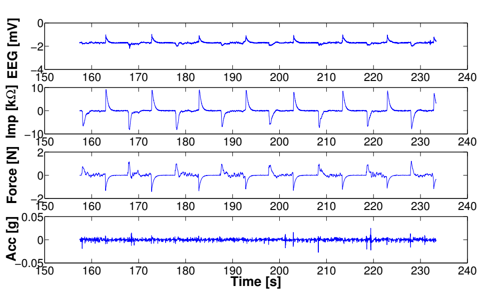
		Con	Rep	Imp	Nod	Til	Sta	Wal	Jum
EEG(mV)	mean	-1.7±0.17	-1.7±0.09	-1.7±0.20	-0.17±0.22	-1.7±0.23	-1.7±0.28	-1.6±0.29	-1.4±0.61
	max-min	3.1±2.41	3.0±3.39	4.2±1.91	2.6±1.25	3.8±2.99	3.3±2.93	11.8±4.77	11.9±3.88
	stdev	0.1±0.06	0.1±0.11	0.2±0.15	0.1±0.11	0.2±0.11	1.5±0.13	1.0±0.67	1.0±0.85
Imp($k\Omega$)	mean	39±21	35±12	41±20	57±23	53±24	52±25	56±27	59±20
	max-min	32±21	23±24	35±21	36±33	28±42	14±12	36±27	94±26
	stdev	8.7±6.5	5.1±3.5	5.9±5.6	7.5±6.8	3.9±5.1	1.5±1	5.3±5.2	7.4±2.5
For(N)	mean	1.5±0.28	1.2±0.25	1.0±0.39	0.8±0.29	0.9±0.26	0.8±0.52	0.9±0.48	0.9±0.53
	max-min	4.5±0.73	3.2±0.89	4.0±1.03	1.1±0.49	1.1±0.38	1.0±0.31	1.5±0.55	3.1±1.18
	stdev	1.0±0.19	0.7±0.18	0.3±0.11	0.3±0.16	0.2±0.06	0.1±0.03	1.6±0.08	0.2±0.06
Acc(g)	mean	0.7±0.06	0.7±0.05	0.7±0.06	0.7±0.05	0.7±0.07	0.7±0.05	0.7±0.05	0.7±0.05
	max-min	0.2±0.07	0.16±0.2	0.3±0.18	0.4±0.12	0.6±0.08	0.5±0.11	0.6±0.17	1.2±0.33
	stdev	0.0±0.00	0.0±0.00	0.0±0.00	0.1±0.02	0.1±0.01	0.0±0.01	0.0±0.01	0.1±0.02

itive force experiment, the tilting experiment and the standing experiment where less severe force changes and rapid motion were involved. One interesting observation is that although nodding introduced less acceleration, the mean impedance value and the peak-to-peak value were relatively higher than most of the other experiments. In external force experiments, the applied forces did not have sufficient influence on the acceleration. Only the peak to peak value in the impactive force experiment reached 0.3. However, because the acceleration created by the impactive force was too short, it was not feasible to use correlation coefficient to indicate the strength of the relationship. Therefore, in the external force session only the EEG, the impedance and the force were used in the cross correlation coefficient analysis.

IV.1.2 High-pass filtering



(a) *Before filtering*



(b) *After filtering*

Figure 4: *The results of the 5s repetitive force experiment of the subject 8 before and after the application of the first order high-pass filter on the impedance and the force.*

Figure 4 shows the results of the 5*s* repetitive force experiment of the subject 8. Figure 4a is the raw recorded data, where the impedance and the force were nicely block-shaped. After applying the first order high-pass filter, the impedance and the force signals showed similar pattern as the EEG signal (Figure 4b).

Table 2 and Table 3 demonstrate improvements in the impedance-EEG and the force-EEG in the continuous force and the repetitive force experiments, where low frequency forces were applied during the experiment. In contrast, in the experiments with rapid force changes and high acceleration, the cross correlation coefficients stayed at approximately the same values.

IV.1.3 Cross correlation coefficient analysis

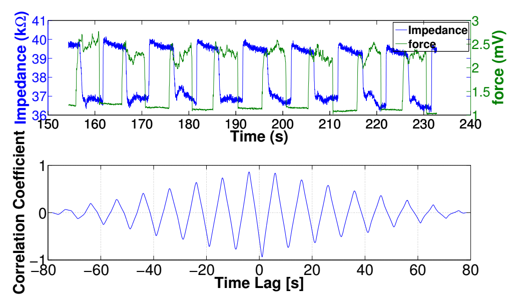


Figure 5: *The cross correlation of the unfiltered impedance and unfiltered force with the period of 5s of subject 9 in the repetitive force experiment.*

Figure 5 demonstrates the cross correlation between the unfiltered impedance and the unfiltered force when repetitive force with a period of 5*s* was applied for subject 9. The cross correlation was plotted with respect to the time lag. The impedance decreased when the force was applied, which can be reflected by the negative cross correlation at around 0 time lag. The cross correlation had a periodic behaviour at around 10 seconds per period, which is same as the force changes. It indicated that the impedance and the force contained similar periodic component. As can be seen, the cross correlation contains an oscillation at the same frequency, meaning that seasonal fluctuations

Table 2: *Average absolute maximal cross correlation coefficients across all the experiments before filtering.*

Correlation	Con	Rep	Imp	Nod	Til	Sta	Sit	Wal	Jum
Imp & EEG	0.56	0.50	0.80	0.62	0.68	0.57	0.53	0.39	0.60
For & EEG	0.55	0.51	0.81	0.59	0.64	0.51	0.51	0.35	0.53
Acc & EEG	0.39	0.51	0.28	0.59	0.69	0.56	0.57	0.35	0.51
Imp & For	0.92	0.92	0.94	0.87	0.73	0.66	0.67	0.40	0.66
Imp & Acc	0.42	0.30	0.30	0.88	0.70	0.67	0.59	0.37	0.59

Table 3: *Average absolute maximal cross correlation coefficients across all the experiments after filtering.*

Correlation	Con	Rep	Imp	Nod	Til	Sta	Sit	Wal	Jum
Imp & EEG	0.70	0.81	0.80	0.62	0.65	0.58	0.57	0.38	0.58
For & EEG	0.66	0.75	0.81	0.59	0.59	0.52	0.54	0.34	0.51
Acc & EEG	0.27	0.16	0.28	0.60	0.65	0.55	0.55	0.32	0.51
Imp & For	0.83	0.85	0.94	0.82	0.70	0.68	0.66	0.43	0.70
Imp & Acc	0.30	0.17	0.29	0.84	0.57	0.72	0.64	0.43	0.62

existed. The cross correlation reached the local peak values when the time lag increased in the order of the applied force (5*s*). As stated in the section III.1, because the impedance and the force were not perfectly aligned in time, the time lag at which the maximal values were reached is only indicative. In the cross correlation coefficient analysis we use only the peak values to indicate the linear similarity strength between the two signals.

IV.2 Intra experiment analysis

IV.2.1 External force

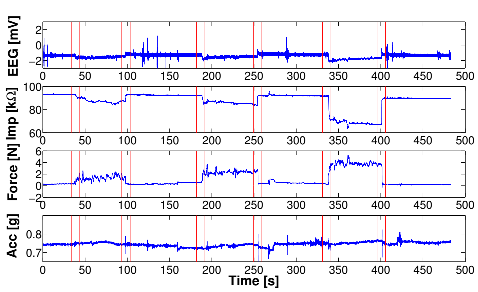


Figure 6: *The EEG and the unfiltered impedance, force and acceleration of subject 1 in the continuous force experiment.*

The EEG and the unfiltered impedance, force and acceleration of subject 1 in the continuous force experiment are selected to demonstrate the influences of the continuous force on the morphologies of the EEG and the impedance (Figure 6). As explained in section IV.1.1, the acceleration could not provide sufficient information in the external force experiments. Only the EEG, the impedance and the force were investigated. The results suggested strong correlations between the 3 signals. It can be seen that impedance and the EEG started to drop sharply when the force was applied. The changes became more evident with increasing the force magnitude. However, different responses were observed in other subjects when force was increased. In some subjects, the influences of the force magnitude were not visible. In some cases, the impedance value decreased gradually when the force was applied. In some subjects instead of stabilizing at a different value, the EEG showed an impulse response before stabilised at around the initial value.

The maximal cross correlation coefficients of 11 subjects in the continuous force experiment are represented in Figure 7. Both positive and negative values could be observed in the impedance-EEG correlation and the force-EEG correlation. Considerably more segments showed positive values in the impedance-EEG and negative values in the force-EEG. In the impedance-force, all the cross correlation coefficients showed high negative values. The absolute values of the impedance-EEG were at around 0.7 (Table 4). The force-EEG showed sl-

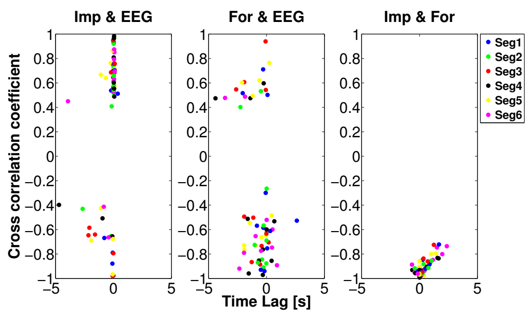


Figure 7: *The maximal cross correlation coefficients of 11 subjects in the continuous force experiment. The results were demonstrated by the segments.*

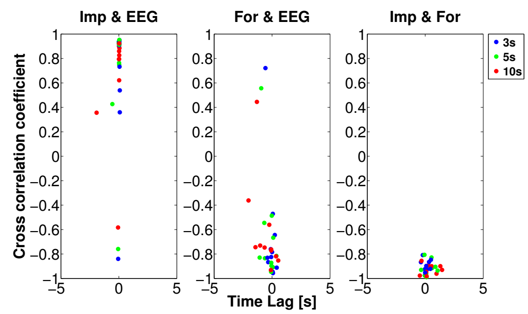


Figure 8: *The maximal cross correlation coefficients of 11 subjects in the repetitive force experiment. The results were presented by the period of the applied force.*

ightly lower correlation with values at around 0.65. The impedance-force had the strongest correlation among the three with values around 0.9. No obvious relation between the force magnitude and the absolute cross correlation values were observed. However, the correlation coefficients values of impedance-EEG and force-EEG were higher in segments where force was applied than in segments where force was released. The highest average correlation coefficients was reached by impedance-force with a value of 0.92 (Table 2). The impedance-EEG and force-EEG had values at around 0.7 (Table 3).

Table 4: *Average absolute maximal cross correlation coefficients in continuous force experiment*

Continuous Force (abs)						
Correlation	Seg1	Seg2	Seg3	Seg4	Seg5	Seg6
Imp & EEG	0.75	0.64	0.74	0.67	0.70	0.68
For & EEG	0.63	0.66	0.68	0.69	0.64	0.67
Imp & For	0.91	0.94	0.92	0.92	0.93	0.88

The cross correlation analysis of the repetitive force experiment was aimed at investigating the influences of the period of repetitive force(Figure 8). The signs of the coefficients were more consistent compared with the continuous force experiment. Only 3 out of 33 segments were negative in the impedance-EEG, and positive in the force-EEG. By further assessing the data, the results indicated that all the three inconsistent segments were obtained in subject 7. Similar as in the continuous force experiment, the force-EEG showed the best correlation between each other with values above 0.9 (Table 5). The impedance-EEG had values at around 0.8 followed by the impedance-force at around 0.75. The impedance-EEG and the force-EEG showed better cross correlations in the segments with shorter force period (3s, 5s). The maximal average correlation coefficients of impedance-force was at 0.92 (Table 2), followed by the impedance-EEG and force-EEG with values of 0.81 and 0.75 respectively (Table 3).

Table 5: *Average absolute maximal cross correlation coefficients in repetitive force experiment*

Repetitive Force (abs)			
Correlation	3s	5s	10s
Imp & EEG	0.82	0.84	0.77
For & EEG	0.79	0.76	0.70
Imp & For	0.90	0.93	0.93

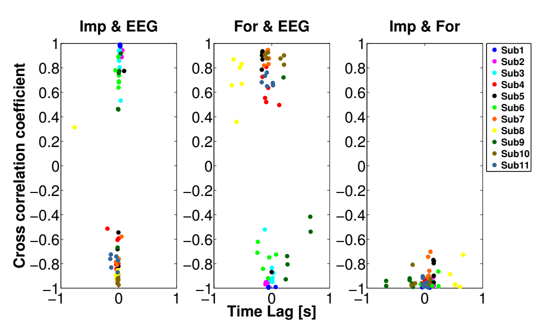


Figure 9: *The maximal cross correlation coefficients of 11 subjects in the impactive force experiment. The results were plotted with respect to the subject.*

Table 6: *Average absolute maximal cross correlation coefficients in impactive force experiment*

	Impactive Force										
Correlation	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Sub7	Sub8	Sub9	Sub10	Sub11
Imp & EEG	0.98	0.91	0.83	0.69	0.75	0.74	0.77	0.77	0.67	0.94	0.78
For & EEG	0.98	0.96	0.84	0.62	0.88	0.76	0.88	0.70	0.69	0.89	0.69
Imp & For	0.98	0.96	0.97	0.95	0.85	0.96	0.84	0.92	0.95	0.93	0.95

In the impactive force analysis, all the three coefficients had high cross correlation coefficient values (Figure 9). However, although the impedance-EEG and force-EEG contain both positive and negative values, the values were consistent for the same subject. In the impedance-EEG, 4 subjects showed positive values in all the 6 segments, 4 subjects showed negative values, 2 subjects had 1 positive value and 5 negative values, and 1 subject had 1 negative value and 5 positive values. In the impedance-force, the cross correlation coefficients showed consistent high negative values. In Table 6, the absolute cross correlation coefficient values were presented with respect to the subject. The cross correlation coefficients varied across subjects. Although in some cases the highest cross correlation coefficient was not obtained by the impedance-force, the impedance-force still showed the strongest correlation with an average value up to 0.94 (Table 2).

IV.3 Head movement

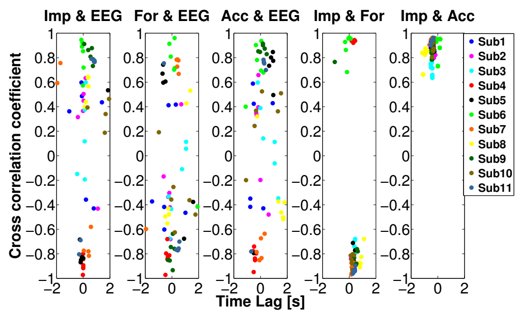
In the head movement experiment, 2 types of head movements were investigated. Figure 3 demonstrates the EEG, the impedance, the force and the acceleration of subject 11 in the nodding experiment. Acceleration started to increase when the nodding started. After the head reached the lowest point the subject started to lift the head. From this moment the acceleration started to decrease. The force had an almost symmetrical pattern as the acceleration. The impedance magnitude followed the opposite trend as the force. When the force decreased, the impedance magnitude started to grow. The peak value of the impedance increased slowly in every nodding movement before it stabilized at around $130k\Omega$. The EEG showed negative correlation with the impedance. It started to drop from the initial value when the impedance started to rise. However, the changes in the EEG were sharper than in the other signals.

The cross correlation coefficients are presented in Figure 10. In the nodding movement, most of the segments had negative correlation in the impedance-force. All the segments had high positive values in the impedance-acceleration. Both the impedance-force and impedance-acceleration had average absolute maximal correlation values at above 0.85 (Table 2). The impedance-EEG, the force-EEG and the acceleration-EEG were at around 0.6 (Table 3), among which the impedance-EEG showed the strongest correlation with a value of 0.62.

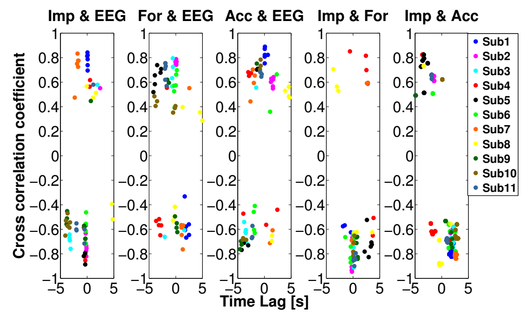
In the tilting movement, all the absolute average cross correlation coefficients values were at around 0.65 (Table 2 and 3). In contrast to the nodding movement, the impedance-acceleration showed more negative values in the tilting movement (Figure 10b). The impedance-force had more positive correlation. Both positive and negative values could be observed in the results. However, the values are rather consistent within the subject for all correlations. Because the head movement in tilting was symmetrical, the oscillations in the signals were also nearly symmetrical. The maximal cross correlation was reached when the right side movement was correlated with the left side movement. This is the reason for the large time lag in a considerable number of subjects.

IV.4 Daily activity

Figure 11 demonstrates the cross correlation coefficients of 11 subjects in the daily activity experiment including standing, sitting, walk-

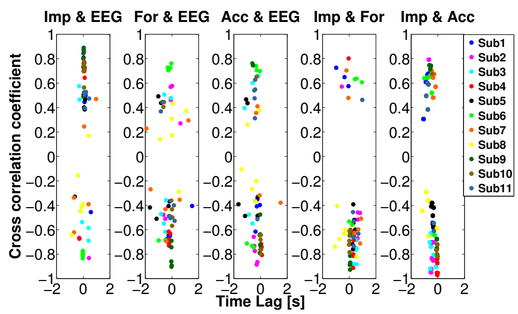


(a) *Nodding movement*

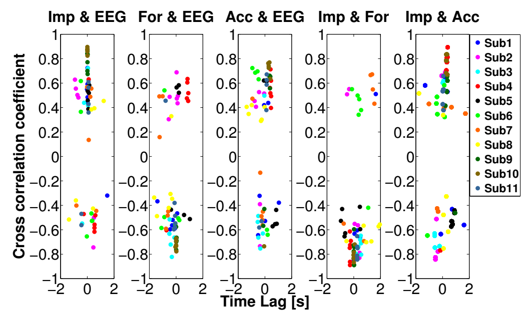


(b) *Tilting movement*

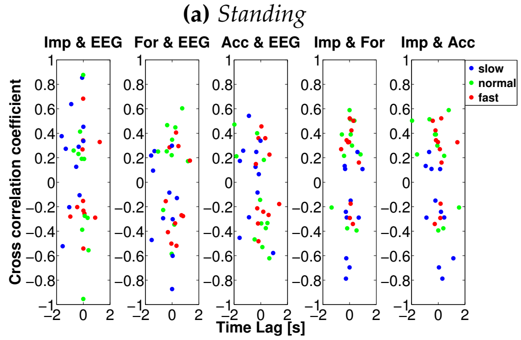
Figure 10: *The maximal cross correlation coefficients of 11 subjects in the head movement experiment. a: nodding movement; b: tilting movement; Imp: impedance; For: force; Acc: acceleration; Sub: subject.*



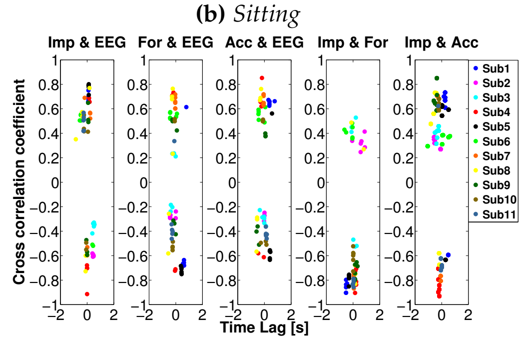
(a) *Standing*



(b) *Sitting*



(c) *Walking*



(d) *Jumping*

Figure 11: *The maximal cross correlation coefficients of 11 subjects in the daily activity experiment. a: Standing; b: Sitting; c: Walking; d: Jumping; Imp: impedance; For: force; Acc: acceleration; Sub: subject.*

ing and jumping. Compared with the external force experiment and the head movement experiment, the cross correlation coefficients were lower.

The nodding experiment showed the strongest correlation between the signals. The impedance-force and the impedance-acceleration had the highest values at around 0.87 (Table 2). The impedance-EEG, force-EEG and acceleration-EEG in nodding were all around 0.6 (Table 3).

The walking experiment had the lowest correlation values between the signals with an average of 0.36. High correlation values could be observed in the impedance-EEG in several segments (Figure 11c). The cross correlation coefficients were slightly higher when subjects walked in the normal speed.

The average absolute cross correlation coefficient values in other daily activities were above 0.5 (Table 2, 3). In most experiments, the impedance-force showed the best correlation followed by the impedance-acceleration. In the correlations including EEG, the best correlation was achieved by the impedance-EEG with absolute values at around 0.6. Apart from the walking, the cross correlation coefficients of the impedance-force and the impedance-EEG showed less flipping in the signs (Figure 11). The impedance-force showed more negative correlations and the impedance-EEG showed more positive correlations.

V. Discussion

V.1 External force

The results of the external force experiment correlation analysis demonstrated strong correlations among the EEG, the impedance and the force. The force magnitude influences the impedance magnitude. In most subjects when the force magnitude applied on the electrode increased, the decrease in the impedance magnitude became more evident. In some subjects this kind of changes could not be observed. This may be due to the differences in the characteristics of the skin and the skin-electrode contact properties. The impedance-EEG and the force-EEG showed higher cross correlation coefficients when the force changed fast. One possible explanation is that the motion artefacts in the EEG and the impedance trend to be stronger when rapid force change occurs. Impedance can be used for motion artefact detection in this case.

V.2 Body movement

The head movement experiment and the daily activity experiment illustrated strong correlations between the impedance and the acceleration, and the impedance and the force. The type of head movement and daily activity influenced the results of the cross correlation coefficients analysis. Especially in the daily activity experiment, the cross correlation coefficient was lower than in the other experiments. However, by visual inspection, correlated changed could be observed. The reason that these correlated changes were not reflected in the cross correlation coefficient could be due to cross correlation coefficient only provides the linear similarity between the 2 signals. It cannot capture non-linear effects. When the motion results in non-linear changes, the correlation coefficient can only indicate to which extent that relationship can be reflected approximately by a linear relationship instead of reflecting an exact functional relationship. Moreover, daily activities resulted in inneglectable cable movements. Hence, additional artefacts were induced through cables and the electronic devices. Compared with the force and the acceleration, the impedance still showed the best linear correlation with the EEG. In these cases, the changes in the morphology or the properties of impedance maybe valuable in building motion artefact detection and removal algorithm. However, further analysis is required.

V.3 Cross experiment analysis

Both negative and positive correlations could be observed in the analysis. In some experiments, this phenomenon even occurred within the same subject. The reason could be due to the distortions in the EEG signal created by the high-pass filter. However, this inconsistency is less obvious in the external force experiment than the experiments including body movements. It suggests that the cable movements could be one of the potential causes of the flipping signs.

In some experiments, although the results included both negative and positive values, the correlation was more consistent for the same subject. This suggests that part of the inconsistency we observed was because of differences in the skin properties which vary from subject to subject. Another important observation was that it happened that one subject could have opposite correlations in different experiments. This suggests that different type of movement and force changes may result in different correlations for the same subject. These effects increase the difficulties in motion artefact detection and removal.

Final observation is that the peak-to-peak value of the EEG and the impedance were higher in the impactive force, walking and jumping. This observation suggests that rapid force changes and fast movement have a tendency to generate larger signal distortions.

V.4 Future application

The fact that the correlation of the impedance-EEG was higher than the force-EEG and the acceleration-EEG in most of the experiments suggests that impedance monitoring is more important for the artefact detection and removal in EEG signals than force monitoring and acceleration monitoring. Impedance can indicate motion artefact in EEG. This information may be further used in adaptive removal of motion artefact [11, 12]. It can also assist in the selection of the appropriate component in independent component analysis (ICA) [13] and in methods that use ICA for artefact removal.

VI. Conclusion and recommendation

The main conclusions are as follows:

- The EEG, the impedance and the force were highly correlated when only external force was applied on the electrodes. The impedance showed stronger correlation with the EEG than the force.
- When body movements were involved these relationships could not be reflected by the cross correlation coefficients due to the non-linear behaviour of the signals. The impedance still showed the highest linear similarities with the EEG.
- Impedance showed the least alternating in the signs of the cross correlation coefficients.
- Impedance is the best candidate to be used to indicate motion artefact in EEG signal.

During the experiments, some limitations were discovered, therefore the following is recommended:

- Because it was impossible to switch off the high-pass filter mounted in the *EEGv*2.0 system, the recorded EEG signal was distorted. It made the investigation on the influences of the external force, head movement and daily activities on the morphology of the EEG signal more difficult. The high-pass filter also affected the cross correlation coefficient analysis. Thus, one further study that excludes the high-pass filter is required.
- The force applied in this experiment was generated by the experimenter. Hence, the application of constant force might not be performed. Usage of force actuator could achieve more accurate and repeatable experiment execution.
- Last but not the least, due to the limitation of the acquisition systems, cross correlation coefficient analysis cannot provide valuable information about the delay between the signals. The setup has to be developed to be able to investigate the delays between signals in the future.

References

[1] T. Sullivan, S. Deiss, T. Jung, and G. Cauwenberghs. A low-noise, low-power EEG acquisition node for scalable brain-machine interfaces. In *Proceedings of the SPIE Conference on Bioengineered and Bioinspired Systems III*, pages 2–4, 2007.

[2] J. Webster. *Medical instrumentation: application and design*. Wiley-India, 2009.

[3] M. Kutz. *Standard handbook of biomedical engineering and design*. McGraw-Hill, 2003.

[4] R. Flink, B. Pedersen, A. Guekht, K. Malmgren, R. Michelucci, B. Neville, F. Pinto, U. Stephani, and C. Özkara. Guidelines for the use of EEG methodology in the

diagnosis of epilepsy. *Acta Neurologica Scandinavica*, 106(1):1–7, 2002.

[5] Emotiv. `http://www.emotiv.com`. Accessed: 21/01/2013.

[6] Neurosky. `http://www.neurosky.com`. Accessed: 21/01/2013.

[7] imec. `http://www2.imec.be`. Accessed: 21/01/2013.

[8] N. Thakor and J. Webster. The origin of skin potential and its variations. In *31st Annual Conference on Engineering in Medicine and Biology (ACEMB), Georgia, Alliance for Engineering and Biology, Bethesda*, 1978.

[9] J. Ottenbacher, M. Kirst, L. Jatoba, U. Großmann, and W. Stork. An approach to reliable motion artifact detection for mobile long-term ECG monitoring systems using dry electrodes. In *IV Latin American Congress on Biomedical Engineering 2007, Bioengineering Solutions for Latin America Health*, pages 440–443. Springer, 2008.

[10] S. Patki, B. Grundlehner, A. Verwegen, S. Mitra, J. Xu, A. Matsumoto, J. Penders, and R. F. Yazicioglu. Wireless EEG system with real time impedance monitoring and active electrodes. *IEEE Biomedical Circuits and Systems Conference (BioCAS)*, 2012.

[11] PS Hamilton, MG Curley, RM Aimi, and C Sae-Hau. Comparison of methods for adaptive removal of motion artifact. In *Computers in Cardiology 2000*, pages 383–386. IEEE, 2000.

[12] DA Tong, KA Bartels, and KS Honeyager. Adaptive reduction of motion artifact in the electrocardiogram. In *Engineering in Medicine and Biology, 2002. 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society EMBS/BMES Conference, 2002. Proceedings of the Second Joint*, volume 2, pages 1403–1404. IEEE, 2002.

[13] Jorge Iriarte, Elena Urrestarazu, Miguel Valencia, Manuel Alegre, Armando Malanda, César Viteri, and Julio Artieda. Independent component analysis as a tool to eliminate artifacts in EEG: a quantitative study. *Journal of clinical neurophysiology*, 20(4):249, 2003.