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Multi-Point Multi-Dimensional Accelerometer Data Logging System for Biomedical Applications

Biyomedikal Uygulamalar için Çok Noktalı Çok Boyutlu İvmeölçer Veri Kayıt Sistemi

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Abstract

Some biomedical signal processing applications require specific data logging hardware. Knee related non-invasive diagnosing and jaw related electroencephalography (EEG) artifact cleaning applications would be good candidates requiring simultaneous multi-channel vibration data logging. In this study, a novel multi-point multi-dimensional accelerometer data logging system was proposed. This system collects three-dimensional tilting and vibration data from three different points simultaneously by using accelerometers. Multi-channel signal analyzing requires simultaneous data recordings for filtering and separating the sensor data into components. The selected accelerometer provides the requirement of simultaneous three axes data recordings. The accelerometer data logging system can be used to obtain tilting and vibration data from knee for diagnosing support and from jaw for EEG jaw artifact cleaning support. Three accelerometers can be placed on kneecap and lateral positions to detect vibrations of knee movements (vibroarthrographic (VAG) signals). The obtained VAG signals can be evaluated by statistical or time-frequency analysis techniques. Also, three accelerometers are placed on face to record jaw and neck movements. Simultaneously recorded EEG and jaw data can be further analyzed by filtering or statistical methods to extract undesired neck and jaw artifacts.

Keywords: *Accelerometers, Vibration measurement, Data logging, Signal Analysis, Biomedical signal processing*

Öz

Bazı biyomedikal sinyal işleme uygulamaları, özel veri kaydı donanımı gerektirir. Diz ile ilgili non-invaziv teşhis ve çene ile ilgili elektroensefalografi (EEG) bozunum temizleme uygulamaları, eşzamanlı çok kanallı titreşim veri kaydı gerektiren iyi adaylar olacaktır. Bu çalışmada, yeni bir çok noktalı çok boyutlu ivme veri kayıt sistemi önerilmiştir. Bu sistem ivmeölçerler kullanarak aynı anda üç farklı noktadan üç boyutlu eğilim ve titreşim verilerini toplamaktadır. Çok kanallı sinyal analizi, sensör verilerini filtrelemek ve bileşenlerine ayırmak için eşzamanlı veri kayıtları gerektirir. Seçilen ivmeölçer, aynı anda üç eksen veri kaydı gerekliliğini sağlamaktadır. İvmeölçer veri kayıt sistemi, teşhis desteği için dizden ve EEG çene bozunum temizleme desteği için çeneden eğilim ve titreşim verileri elde etmek için kullanılabilir. Diz hareketlerinin titreşimlerini (vibroartrografik (VAG) sinyaller) tespit etmek için diz kapağı ve yan pozisyonlara üç ivmeölçer yerleştirilebilir. Elde edilen VAG sinyalleri, istatiksel veya zaman-frekans analiz teknikleri ile değerlendirilebilir. Ayrıca çene ve boyun hareketlerini kaydetmek için yüze üç adet ivmeölçer yerleştirilmiştir. Eş zamanlı olarak kaydedilen EEG ve çene verileri, istenmeyen boyun ve çene bozunumlarını çıkarmak için filtreleme veya istatistik yöntemler ile daha ileri bir şekilde analiz edilebilir.

Anahtar Kelimeler: *İvmeölçerler, Titreşim ölçümü, Veri Kayıt, Sinyal analizi, Biyomedikal sinyal işleme*

1. Introduction

In addition to various industrial applications, accelerometers can also be used in biomedical applications related to measurement of motions including acceleration, speed, and position information [1-2]. In this application area, vibration information can be obtained from accelerometers and this information can be applied in diagnosis of non-invasive knee-joint problems or in cleaning of motion-based artifact sources in EEG signals.

Knee-joint problems exist especially at older ages. Methods of X-Ray, MRI and an invasive method of arthroscopy can be used for diagnosis. Developing of a non-invasive diagnosing method for knee-joint problems requires a vibration signal recording hardware and software. These knee related vibration signals are called vibroarthrographic (VAG) signals [3-4]. They can be used to identify healthy or not healthy human knees and joints. These vibration data include some useful information which relate to joints especially knee problems.

So far, a number of studies have been carried out in the field on knee VAG signal identification and analysis [5-22]. These studies show that, the use of accelerometers was preferred to stethoscopes and microphones because of their insufficient low frequency responses in defining knee related problems. However, only a single axis accelerometer does not provide sufficient information as VAG data. Now, with currently available Micro-Electro-Mechanical Systems (MEMS) technology [23-24], it is possible to use enhanced three axes accelerometers. In this study, we have proposed and designed a multi-point multi-dimensional (MPMD) accelerometer data logging system (ADLS) by using enhanced three axes accelerometer modules [25-26].

Multi-point simultaneous accelerometer data logging is very useful for increasing the performance of analysis. Real-time data logging from multi-points is especially required for tracing time trends of multiple locations. The analysis can be processed during or after data logging. Simultaneous data recording from multiple points is needed to achieve comparison of multi-points data with each other in the same time instances. For the vibration data analysis, Independent Component Analysis (ICA) [27] can be used to remove noise and unwanted signal forms from knee recordings to extract the desired signal source(s). Then, the obtained chosen signals can be used for diagnosing purposes. Our accelerometer data logging hardware and software is suitable for ICA analysis which, preferably, needs to have simultaneously recorded multi-point data.

Another application area would be filtering of jaw artifacts from electroencephalography (EEG) recordings using simultaneously recorded vibration data from human jaw. These supporting data would help to filter jaw motion-based artifacts effectively from EEG recordings without losing the important information on the EEG signals.

2. Material and Method

The knee study is in testing phase and the data was collected from the author's knee itself. The jaw study made use of biological data obtained from Dokuz Eylul University Faculty of Medicine. The jaw recordings were realized in Biophysics Dept., Brain Biophysics Laboratory. Four subjects (males, 24-40 years, healthy) volunteered to participate to jaw analysis study.

The main aim of the designed data logging system is to develop a non-invasive measurement technique to address various motion related issues in the human body. Two schemes have been adopted as knee model and jaw application. The first one is targeted on diagnosing in order to identify knee related problems especially arise in older ages. The second one is related to EEG artifact cleaning.

2.1. Accelerometer Data Logging System

The MPMD ADLS consists of two main parts:

i) accelerometers, and

ii) a controller electronic board

The designed MPMD ADLS system block scheme is shown in Figure 1. The heart of the MPMD ADLS is based on a USB PIC microcontroller [28]. A Microcontroller is needed to collect three accelerometers' data simultaneously and store or send them to a desktop or mobile personal computer. Also, the ADLS system circuit board has 5V and 3.3V voltage regulators, 3.3V-5V level translators, current buffers, a real time clock circuit, LCD screen, and SD card interface circuit.

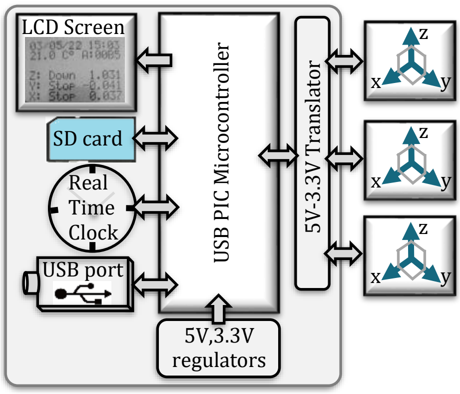

Figure 1. Accelerometer Data Logging System Schematic

In the developed hardware system, three axes accelerometer module LIS3LV02DQ [29] from ST Microelectronics was used to collect accelerometer data. This accelerometer which has a user selectable full-scale conversion of ±2g, ±6g simultaneously converts three axes acceleration data. It has the capability of measuring acceleration over a bandwidth of 640 Hz for all axes. The communication protocol can be I2C or SPI for the microcontroller interface. The possible applications are free fall detection, inertial navigation, virtual reality input devices and vibration monitoring and compensation.

The designed system is illustrated in Figure 2. Three accelerometers are placed on an elastic band to collect data from kneecap and two lateral positions. The same elastic band fits also to jaw locations. The microprocessor-based controller unit is located on a printed circuit board and mounted on a plastic case. On the controller board there is an LCD display and an LED to illustrate the currently collected data and working status of the controller, respectively. USB cable from a PC is connected to the USB port of the system for data transfer and power supply.

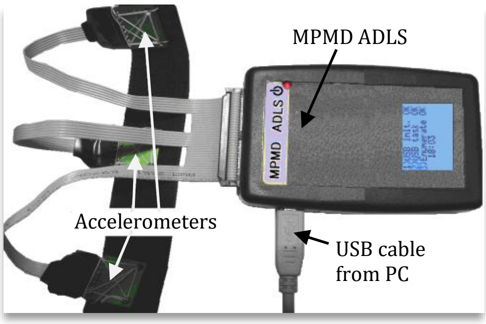

Figure 2. Photo of an Accelerometer Data Logging System

The currently developed MPMD ADLS supports up to four accelerometers simultaneously. However, the number of supported sensors can be easily increased by upgrading the buffer hardware. PIC microcontroller collects data from accelerometers and transfers them to a mobile computer with USB 2.0 interface. Three axes' data from each three accelerometers means nine channels of data need to be acquired. This sized of data collection is better achieved by USB interface rather than available RS-232. The LCD screen shows accelerometer results, processing steps, and time stamps. The collected accelerometer data were transferred to the PIC microcontroller memory via serial peripheral interface (SPI) bus.

A microcontroller based real-time operated system has been developed in C programming platform to achieve high speed USB data transfer to a mobile computer. Here, USB 2.0 guarantees enough data bandwidth for real time operation and mobile operability without using an RS232 serial port.

Additionally, a mobile computer software has been developed on MATLAB platform to achieve robust data logging and analyzing on the same program code. The MATLAB software communicates with ADLS via USB and shows collected data on screen and stores them to the RAM memory or hard disk at real time. Moreover, data analysis can be processed at real time or any time after data collection has finished.

2.2. MPMD ADLS and Computer Software

The software of the MPMD ADLS system is based on two platforms: USB PIC microcontroller and computer. The software schematic is shown in Figure 3. On the MPMD ADLS part, the microcontroller software collects three accelerometer data simultaneously, forms a data packet in a defined protocol format and sends them to a Personal Computer (PC) or mobile computer using on-board USB interface. An on-board USB unit provides the advantage of speed and space over many currently available systems with RS232-USB converters.

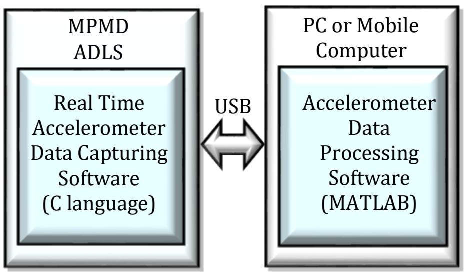

Figure 3. The Software Schematic

The most important specification of the microcontroller software is to send a read command to all accelerometers at the same time and to read the accelerometer data simultaneously. Also, as a hardware the selected accelerometers are clocked with the same clock signal and the data from accelerometers read by at the same time. This ensures the main requirements for the success of the ICA technique.

A data packet, which consists of 15 bytes of accelerometer data is transferred to a mobile computer via USB interface without making any processing on them. This data packet includes checksum byte and PC, or mobile computer controls the checksum to ensure the data received is not corrupted during data transfer. Therefore, data sending and receiving control are performed to guarantee synchronous data transfer between microcontroller and PC or mobile computer.

The READ command from the computer initiates data reception from data logging system and the STOP command from the computer cancels data transfer and puts data logging system into a waiting state. The general algorithm of the microcontroller software is in shown in Figure 4.

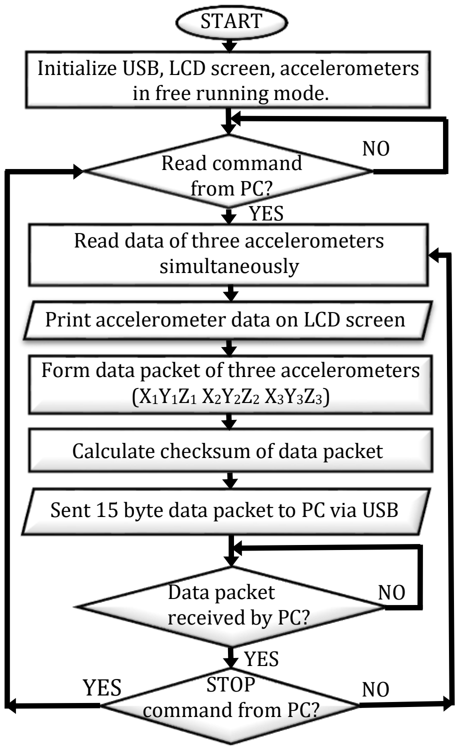

Figure 4. Algorithm of the microcontroller software

A MATLAB graphical user interface (GUI) was used to obtain data from data logging system and for its storage on computer disk. The developed GUI program provides real time or offline data visualization and analyzing option. Figure 5 shows the MATLAB software main graphical user interface (GUI) screen. On the main screen, there are some buttons, option, or list selections, and displays to provide a user-friendly interface.

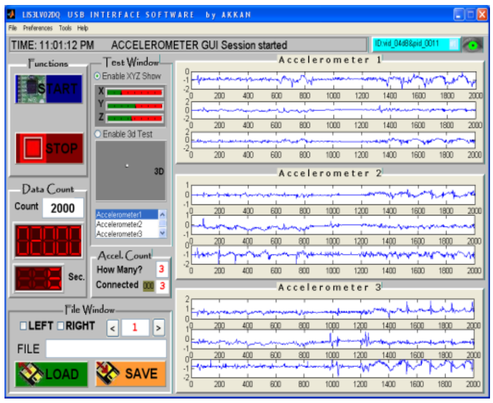

Figure 5. The MATLAB software GUI

The START and STOP buttons initialize and finalize the data logging process. The number of samples is collected in accordance with the provided count number. The number of accelerometers to be used can be selected from the “How Many?” edit box and number of accelerometers physically connected is shown on “Connected” edit box. Previously collected data loading from memory and saving the currently collected or edited data to memory is controlled from the file window. For test purposes, all accelerometers’ data can be visualized in two- or three-dimensional illustration. Accelerometer time trends are shown in real-time on the main screen visually.

Currently available MATLAB graphical components such as numeric displays or bar and three-dimensional graphics are comparatively slow processes and thus may affect the overall real-time software performance. However, graphical user interface is important for visualization. In this study, ActiveX visual components were used for speeding up the graphical update instead of readily available MATLAB components.

The MATLAB software opens two USB communication tunnels for reading and writing data and examines whether USB data logging system is connected or not. If the system is connected, then the system USB identity is verified and the software runs online, and if not, the software enters the simulation mode for testing or analyzing pre-recorded data.

2.3. First Medical Application: Knee

The undesired signals caused by movement of a knee, sensor-skin surface interactions, and muscle contractions can be removed from the recordings and the desired VAG signals for diagnosing of knee problems can be obtained by using Time-Frequency analysis. Important to note, the VAG signals are non-stationary. Therefore, time-frequency analysis is very powerful on this kind of analysis. Moreover, as a statistical method ICA can be useful to extract components of VAG signal for signal filtering purpose. We assume that, with the proposed MPMD ADLS system, it will be possible to utilize ICA, especially, to extract the signal of interest from the accelerometer sensor array. Diagnosing knee problems with the vibration analysis on the kneecap and lateral locations would be possible with the data logging system.

Analyzing the structure of the knee joint is important to define the source of vibration signals. The naturally frictionless system of knee contains the synovial fluid, articular cartilage, and supporting bones [30]. Synovial fluid is important for lubrication, and it also provides a medium for the propagation of vibration signals. As a result, vibration signals obtained from normal knee will be exempt from the additive vibration signals caused by problems.

Analysis of the knee joint movement is also very important to understand the nature of the vibration signals. The main muscles responsible for the knee joint movement are the quadriceps and hamstring muscles. The quadriceps is attached to the patella, and the patellar tendon connects this muscle to the front of the tibia. When the quadriceps muscles contract the knee extends. In contrast, when the hamstring muscles contract, they pull the knee into flexion. It is clear these mentioned muscles contraction will take part within the VAG signal.

The repetitive movement of the leg can be achieved in two steps:

a) The movement starts from a position of the foot resting on the ground and continued rising the foot upwards. The movement ends at an angle smaller than 90° because of the limitation of the knee joint.

b) The reverse movement is achieved from top to the ground.

The speed of the movement is also important. Though smoother movements can be obtained at high speeds, the resolution of the vibration recordings may be reduced. The resolution can be made higher, but more discontinued movements may appear at slow speeds. A person can be assisted while performing up-down movements during recording procedure. However, a mechanical system may be proposed to be built for supporting the knee movements in an adjustable knee movement angle without forcing the limits of the knee and adjustable knee movement speed. Repeating the recording procedure at least three times is required to avoid recording problems and select the best recording. Two accelerometers can be used for knee recording: one for vibration recording and one for y axis tilt angle reading. But for the ICA, it is more appropriate to use three accelerometers. Moreover, the angle information is obtained from the accelerometer located on the knee cap.

2.4. Second Medical Application: Jaw (The temporomandibular joint)

As a further biomedical use, the temporomandibular joint (TMJ) was chosen. The MPMD ADLS system is designed to be functional in different kinetic applications. The straps and the accelerometers properly fixed to the jaw while the data logger box attached to the chest. Jaw movements are accepted as artifact, and therefore must be removed from EEG recordings. The accelerometer is a proper sensor selection to identify jaw related EEG artifacts. Here, we propose MPMD ADLS to be used to record jaw movements concurrently with electrophysiological recordings.

3. Results

In this study, the multi-point multi-dimensional accelerometer data logging system was constructed and applied in two groups. The first application was related to knee movement while the second was focused on jaw (TMJ) movements. The data logging system sensor band attachment to the knee and jaw was successfully achieved without any problems.

The positioning of the three accelerometers to a kneecap and to lateral positions is given in Figure 6. Here, while a person is moving the leg from the ground to a certain upward position, vibrations inside the knee and the angle position of the leg in respect to the initial resting position are collected and transferred to a mobile computer for analysis.

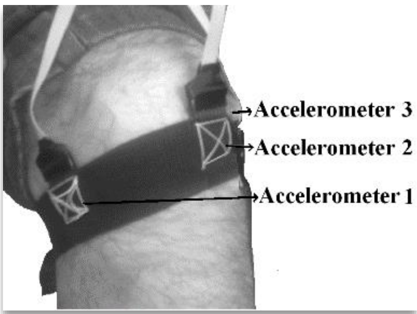

Figure 6. The photo of the three accelerometers connections to the knee.

For clearly understanding how accelerometers are connected to the knee, Figure 7 shows the position of the accelerometers for the right leg and illustrates the leg movement.

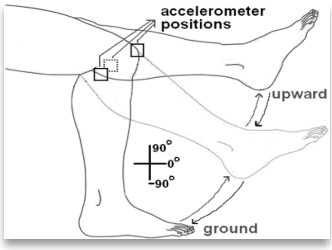

Figure 7. The movement of the leg during recording.

Two accelerometers can be used for knee recording: one for vibration recording and one for y axis tilt angle reading. But for the ICA, it is more appropriate to use the three accelerometers for vibration recording. Moreover, the angle information is obtained from the accelerometer located on the knee cap.

Using the abovementioned experimental setup, the three channel vibration data was obtained from the author knee as a testing purpose with an MPMD ADLS for the duration of 8,000 sample counts (400 samples per second).

Nine channels of logged raw data were obtained from knee movements. Each consecutive three signals representing vibrations on the x, y, and z axes directions derived from a related accelerometer. Thus, there were a total of nine signals. The signal amplitudes showed the g-force in the range of -2g to 2g for the recorded time interval of 20 seconds. Each signal shows a periodic-like behavior representing the knee movements, in the direction down to up and up to down. The crest corresponds to the extended leg position, whereas the trough corresponds to the flexion position. For better understanding, a small part of the x axes data from each accelerometer is illustrated in Figure 8.

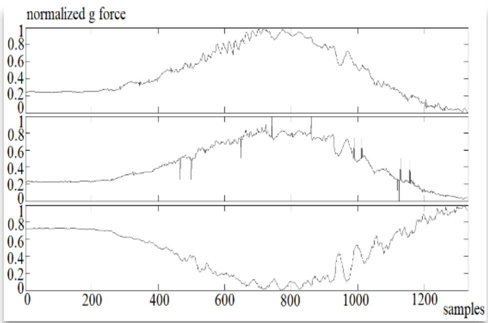

Figure 8. Three channels knee raw data

The actual vibration data were superimposed on the tilting data and the low frequency component shows the leg movement upwards and downwards. This low frequency component can be found using a running average algorithm. The tilting information was filtered out using a running average algorithm to obtain the vibration data alone. The vibration information is shown in Figure 9.

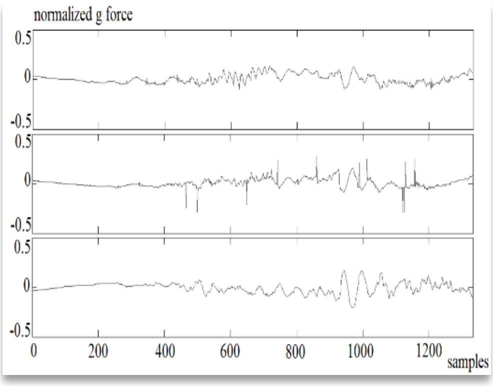

Figure 9. Three channels of knee vibration data

From Figure 8, analyzing the graphical trend of the knee raw data shows that we can extract the knee angular position information using running average algorithm. The first and second channels are good candidates to calculate the knee angle. Usually, this kind of angular measurement can be achieved using mechanical goniometer added as another sensor to the knee. But using already installed accelerometer data, the need of using mechanical goniometer easily eliminated. The trend data on each channel is shown in Figure 10 with thick lines. It is obvious that the person can't move knee in linear trajectory.

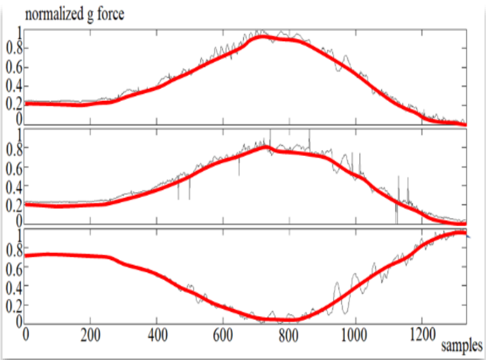

Figure 10. Three channels of knee trend data

The collected data can be processed with this angle information to eliminate this nonlinearity, but it is hard to implement. Therefore, instead of manual leg movement (i.e., up, and down), specifically designed mechanical system can be used automatic movement of knee to ensure that the standardized measurement acquisition.

For further clarity, 3D images of accelerometers are provided in Figure 11. The upper plot is related to the 3D plot of unfiltered signals (tilt and vibration data together), the lower plot is related to the 3D plot of filtered signals (only vibration data). Furthermore, eigenvalues are illustrated on the right side of each 3D plot with bar graphs. These plots can give information how to define the distinctive features of knee data.

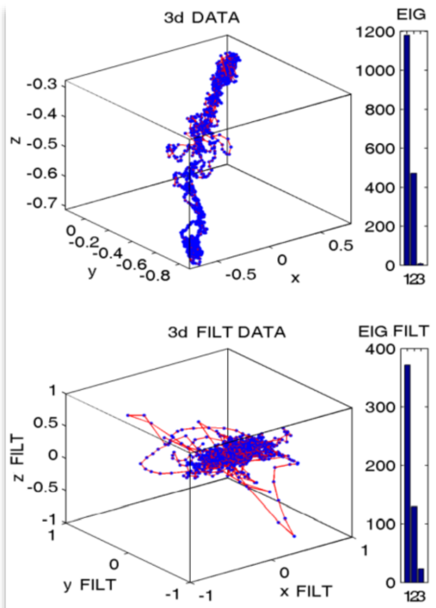

Figure 11. 3D plot of raw and filtered normal knee data

As a further application we propose the artifact rejection applicability in line with electrophysiological recordings of the head namely EEG. In this aspect currently various filtering and blind separation methods are used to clean so called artifacts. Some of these artifacts are based on muscle activity, eye movements, eye blinks, electrocardiogram, respiration, skin conductivity changes, properties of EEG electrodes, dynamic salt bridge formation, and undesired power line 50

Hz [31-32] noise (60 Hz in US). In order to clean such artifacts clearly, EEG signals should be recorded together with some extra signals carrying information related with the artifact occurrences. These additional signals are used to identify the location of artifact formations on the recorded EEG signals. For this purpose, a proper sensor must be used for each specific artifact recording in addition to EEG electrodes. For example, electro-oculogram recordings are used to remove eye-blink artifact. The jaw (TMJ) movements are also regarded to be a major source of artifacts, and therefore must be removed from all EEG recordings. The accelerometer is a proper sensor selection to identify jaw related EEG artifacts. Here, we propose MPMD ADLS to be used to record jaw movements simultaneously with EEG recording electrodes. Figure 12 shows the accelerometer placements on the subject's face attached to the jaw and chin.

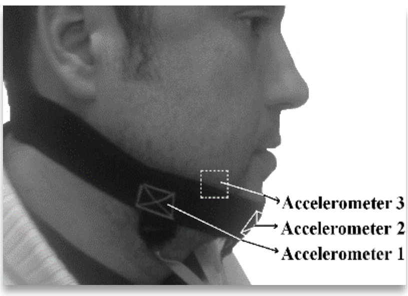

Figure 12. Connection of three accelerometers to the jaw.

Using the mentioned jaw experimental setup, three channel vibration data was obtained for the duration of 20 seconds. Nine channels of logged raw data from jaw movements are obtained. Here, during recording the subject made various jaw movements. Figure 13 shows the selected axes (x axis from accelerometer one, z axis from accelerometer two, and x axis from accelerometer three) data from each accelerometer for the 8,000 sample recordings. First and third accelerometers were placed on the temporal areas of the jaw, and the second accelerometer was placed on the chin. The up and down vertical movements of the head can be seen more clearly between 0 to 3,000 samples (A mark on the Fig. 13). However, between 3,000 to 5,000 samples, the head moved only from left to right and vice versa (B mark on the Fig 13). Therefore, a constant signal level is expected at this interval. However, very small signal fluctuations are seen in this interval probably as a result of moving the head slightly up and down simultaneously. Corresponding to the section falling after 5,000 samples, the subject loudly speaks out some numbers without any head movement (C mark on the Figure 13).

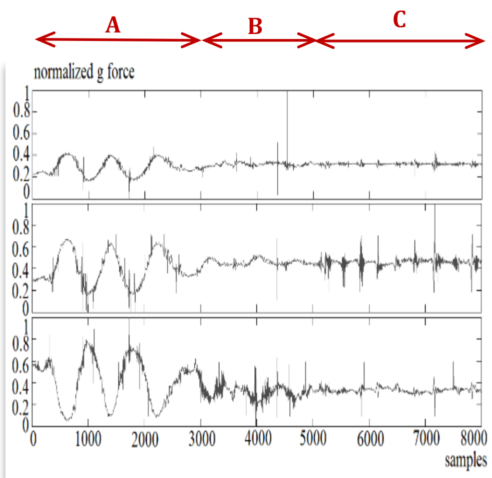

Figure 13. Three channels vibration raw data from jaw.

For each x axis of each accelerometer a running average algorithm is run, and the obtained head movement related data is extracted from the corresponding channel and given in Figure 14. This information is now related with jaw movements and independent from head movements.

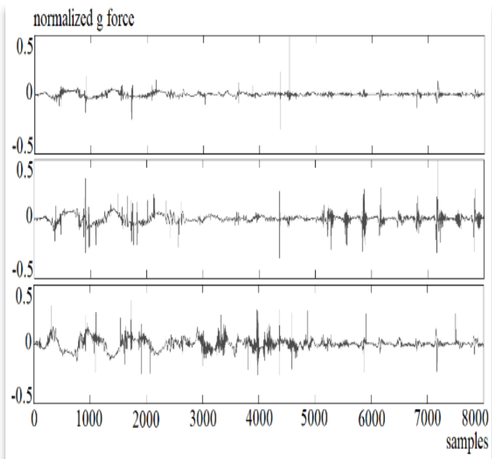

Figure 14. Jaw vibration data.

4. Discussion and Conclusion

The MPMD ADLS has been effectively constructed and applied to knee and jaw areas in order to assess its applicability. The multi axes digital data recording has enabled a line of analysis which might prove to be useful for clinical use. The system main difference from the current accelerometer data loggers is the novel hardware allows multi accelerometer connections with synchronous data logging feature. This synchronous sensor reading is very important to apply statistical analyze methods such as ICA successfully. Statistical analysis such as ICA and furthermore time frequency analysis can be the future applications of the developed system.

Analyzing the knee movements, the baseline signal may explain the general movement properties of the joint. Here the degree of movement as well as the speed can be determined. Thus, this feature may be proposed to compensate the need to use of a goniometer. The secondary and more meaningful data seems to be originating from the fast components. The spike formations deserve to be investigated in detail for pathognomonic assessment. The occurrence rate, the magnitude, the frequency components can serve as features to be extracted. Additionally, the statistical properties of data (mean, variance, kurtosis, etc.) and spectrograms and wavelet analysis of data can be useful features for data analysis.

In the article by Shen et al. (partially similar to the proposed one) device with goniometer and multichannel simultaneous recordings was introduced [5]. In their study, vibration sensors are single dimensional and analogous type. However, the current study uses multi-axes and digital accelerometers without need of additional goniometer. Our proposed system is a multichannel multi-dimensional simultaneous data logging system. This means, nine channels of tilting and vibration information from three accelerometers can be used. The tilting information is useful to detect the knee position and therefore there is no need to use a goniometer. All accelerometers are placed on the kneecap and two sides of the knee in order to diagnose various knee problems sourced from not only the kneecap also lateral positions. Moreover, the proposed system is a standalone multi-channel data logger with/without computer connection.

The system has been designed as a standalone modular system with reduced chip count, low energy consumption, and high-speed computer connection for flexibility and mobility. The communication between MPMD ADLS and the computer is performed either in real-time or offline by using the USB 2.0 connection standard. This provides high speed data transfer, system power supply and allows the realization of real-time operation. The designed data logging system has a flash SD card memory to store large vibration data with their recording date and time stamps up to 1GB capacity.

VAG signal data acquisition from knee was achieved and vibration data and knee movement angle data were successfully extracted. There are numerous knee related problems, and this requires creating a large data base from different cases to obtain data features for developing a convenient classification algorithm such as signal processing or machine learning algorithms. The VAG signal analysis cannot be performed by the currently designed MPMD ADLS because of the current microcontroller's processing power. When various knee data is collected and a useful algorithm is developed to identify normal and problematic VAG signals, it would be possible to use more powerful microprocessor(s) to realize on-board real time analysis by MPMD ADLS.

The preliminary application of the system to the jaw demonstrated the applicability of analyzing this type of movements which can cause serious artifacts during electrophysiological recordings. The recorded trace enabled analysis of the movement. The differential analysis also permitted to analyze the jaw movement discarding the head tilt. Therefore, the system seems to be capable of performing different experimental procedures. The synchronous data logging parallel to EEG recording will be the second line of research study that is planned in the future. The possible applications include not only vertical head-jaw movements but also the body positions in sleep etc.

In this study, the multi-point multi-dimensional accelerometer data logging (MPMD ADLS) system with its complete hardware and software units has been successfully realized for mainly two biomedical applications. The designed system has been developed for the needs of an expert system which supports medical diagnosis of knee joint problems non-invasively.

Moreover, the system could also be used for another human body joint namely the jaw in addition to the knee application. The technique for recording of these jaw movements during the EEG recording to eliminate the jaw artifact (a common problem encountered in EEG labs) more effectively may be extended with various applications such as in sleep.

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