Chapter 2

Signal Acquisition and Database

This chapter provides an overview of EMG signals, associated physiological processes, signal recording, acquisition setup and signal analysis. At the end, it explore the details of real-time data sets used in this study. In particular, the chapter is categorized as: (i) EMG signal, (ii) generation and structure of EMG that help understanding the morphological patterns of MUAP, (iii) EMG signal analysis that gives the indication of morphological changes in signal patterns during pathological conditions and (iv) datasets description.

2.1 EMG signals

Electromyography is an electrical manifestation of the neuromuscular activation associated with the contracting muscle controlled by the central nervous system It is obtained by recording the potential (i.e., voltages) associated with the electrical currents generated in a muscle during contraction. The nature of EMG signals relies on the anatomical and physiological properties of muscles and measuring instrument. It represents the summation of electrical activities of muscle fibers in muscles. Therefore, profound understanding of signals, i.e., how the signals reflect certain mechanisms and phenomena and identifying and describing them is vital requirement in biomedical engineering [101].

Clinical diagnosis and biomedical applications are main reasons of interest in EMG. The shapes and firing rates of MUAPs, which are key components in EMG signals, provide the significant information about the anatomy and physiology of muscles. Appropriate understanding of signals and findings not only help promoting the conventional clinical practice to diagnose diseases but also promote neural control based applications. Therefore, researchers have focused in searching the better algorithm by upgrading or improving existing methodologies and detection techniques which can work efficiently in diverse applications.

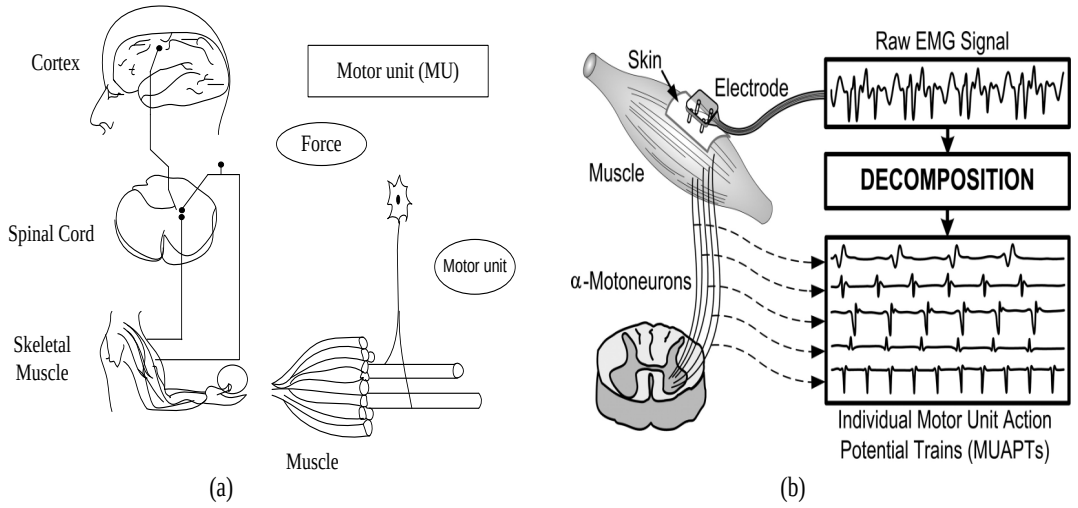

Fig. 2-1: a) Basic motor control mechanisms of the motor unit and its components [102]; b) Typical EMG pattern with MUAP trains [103]. Note that our analysis involves intramuscular EMG.

2.2 Generation and structure of EMG signal

Understanding of EMG and its compositions require the knowledge of an anatomical and functional aspect of the neuromuscular system. The nervous system that composed of brain, spinal cord, and peripheral nerves, controls and communicates different activities of the body. It comprises of avalanche number of small cell, known as *neurons* which communicate with different parts of human body. The neurons, the basic structural units of the nervous system conduct messages in the form of nerve impulses or electrical signals from one part of the body to another part. Fig. 2-1 shows the basic control mechanism of motor unit and generation of EMG pattern.

The muscle is composed of large cells that provide contraction and relaxation to the muscle. The function of such cells is to generate forces for movements and other activities of body. The cell has also ability to receive and respond stimuli which can be contracted. Three types of muscle tissue include in this mechanism - skeletal muscle, cardiac muscle and smooth muscle. EMG is used to study the skeletal muscle, which compose of a large number of parallel muscle cells called muscle-fibers, each of which has the electrical activity. Motor unit is the functional unit of muscle and is defined as the association of a motoneuron α (nervous cell) and the muscle fibers. Both excitable cells - nervous cells and muscle fibers react to all external events that are electrical, mechanical and chemical in nature. These cells have the electrical polarity on both sides of cytoplasmic membrane (membrane potential or resting potential). The measured membrane potential is stable with time and it falls in the range of -70 to 90 mV according to cell type, known as action potential that propagates along the length of the fibers. Relaxation occurs while α-motor neuron ceases activity [104].

A MUAP is the sum of all action potentials generated due to contraction of

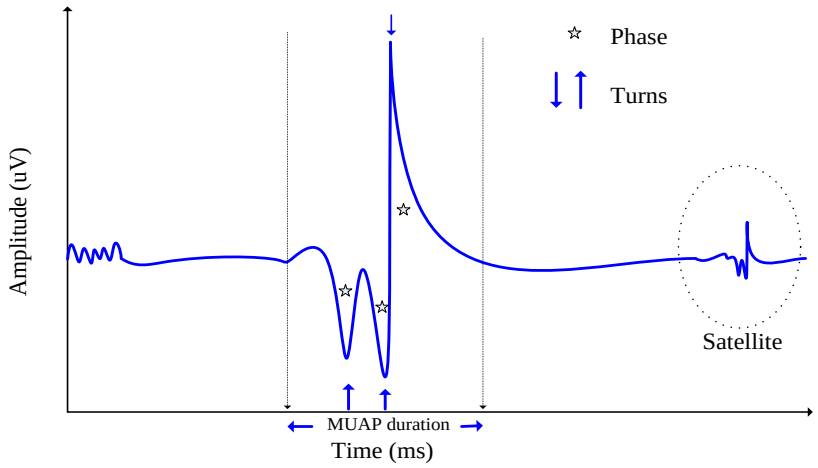

Fig. 2-2: Typical MUAP pattern and its associated features including duration (ms), amplitude ($\mu V/mV$), phase, number of turns, turn ratio etc..

muscles fibers in an MU. It is recorded either by inserting fine needle electrode to the muscle or surface electrode placed on the skin of underlying muscle. The time-course representation of EMG or train of MUAP is as follows:

$$V_{EMG}(t) = \sum V_{MUAP}(n)(t) + \eta(t) \tag{2.1}$$

where $\sum$ and $\eta(t)$ indicate summation of multiple train-MUAP in MU and associated total noises which may arise from many sources. The assessment of MUAPs is essential for key characterization of the electrophysiological properties associated with the muscle. It requires signal decomposition method to study the structure, organization and functional aspect of individual MU. The decomposition involves the acquisition, segmentation, feature extraction, clustering of detected MUPs and MUP assignment. It helps analyzing the contribution of individual MU within the acquired signal [105–107]. Before reviewing the various steps of EMG, it is essential to study the contributions of each active MUP train. Subsequent analysis of firing pattern of each MU along with morphology of MUAPs provides many information. The morphological patterns of MUAPs forming train of MUAP depend on anatomy and physiology of muscle along with electrode placement, study muscle etc. Fig. 2-2 shows the MUAP morphology.

2.3 EMG acquisition

In conventional clinical practice, needle EMG is extensively used for assessment and characterization of neuromuscular disorders including peripheral nerves, anterior horn cells, neuromuscular junctions and muscles. EMG findings are used as complementary measures to the nerve conduction studies (NCS) which adequately helps assessing various disorders in most electrodiagnostic (EDX) evaluations. The analysis requires sound subjective knowledge and skill. In addition to an efficient analysis, acquisition

of reproducible high-quality EMG recordings which in fact depends on a number of factors-insertional needle position, muscle site, needle movement, electrical environment, assessment of clinical problems, are also primarily required [108]. Secondly, the analysis involves multiple responses which have to be analyzed through a skillful approach for final interpretation. The objective and role of EMG analysis in brief are-(i) assessment of MUs including lower motor neuron, neuromuscular junctions and muscle, (ii) complements NCS in localization of neuromuscular disorders, (iii) assessment of temporal profile and activity of neuromuscular disorders and (iv) identification of specific spontaneous discharges.

2.3.1 Signal recording and parameter setting

Special attention to each aspect of EMG ensures an efficient recording of the electric activity from muscle to provide the comfortable and reliable study. Skill of electromyographer has also a lot to do. Several issues such as skin infection, bleeding disorder etc. are also considered prior to the examination.

2.3.1.1 Skin preparation

The neurophysiologist informs the subject about the recording procedure and mild discomfort that may arise during needle insertion. These information are helpful for necessary cooperation for smooth acquisition of signals. During examination, the neurophysiologist focus on a number of parameters such as muscle selection, needle insertion, needle movement etc.

The muscles to be tested is selected on the basis of clinical hypotheses. The distribution of findings often varies in different regions of muscle. With variation in location, the method of activation of muscle greatly changes the findings. Therefore, the examiner's focus is to test each muscle and range of normal findings within the muscle. After proper identification of muscle, the skin is wiped over each puncture site with alcohol. The muscle is palpated during intermittent contraction to localize its borders. The skin is pulled taut to decrease the pain that occurs during insertion of needle through skin. Following removal of the needle after insertion, the muscle is pressed to reduce bleeding.

2.3.1.2 Electrodes and recording technique

EMG recording is performed using a concentric or monopolar needle electrode as shown in Fig. 2-3. Three typical recordings are insertional, spontaneous and voluntary activities. The electrode primarily records activity from a small area of selected muscle

and then move to various positions of muscle to investigate the underlying changes in MUs. While collecting the recordings, the needle is moved vertically into the muscle in slow steps (0.5-1 mm) to avoid the discomfort of the subject. In this way, the examination is performed to collect the recordings for complete assessment. The standard signal recording set up shown in Fig. 2-4 includes signal input, signal processing, signal output, and storage and data management system (SDMS).

In signal input step, recordings are done with a connection of in-built three-electrode system (active, reference and ground) and an external temperature control probe. It is being touch-proof for patient safety. Signal conditioning circuit, i.e., signal processing unit, includes differential amplifier with high gain (sensitivity), filters and analog-to-digital converter (ADC). The conditioning circuit plays an inevitable role in the field of bio-medical instrumentation. Usually most bio-medical detection and measurement designs employ instrumentation amplifier (e.g., INA128P) due to its high precision, ability of low-level signal amplification, high gain $G = 1 + \frac{50k\Omega}{R_g}$ where R_g is gain control resistor in $k\Omega$, low power consumption; high input impedance (i.e, $> 10^3$ MΩ) to prevent loading effect, high common-mode rejection ratio (i.e., $>$ 120 dB) and high slew rate (i.e., 4 V/μS) [109]. Such instrumentations include EMG, electrocardiogram (ECG), NCS and electroencephalogram (EEG). The differential circuit amplifies the potential difference between the active and reference inputs (μV) to improve the signal-to-noise ratio (SNR). Further, it has channel selection mechanism if multiple channels are needed. It has the ability to acquire the signal in the range of 1 μV-50 mV. The analog gain stage consists of a minimum of 3 analog gains (digital amplification increases noise significantly and can mask the biological signal.) The amplifiers use a band-pass filter with adjustable frequency range (cut-off level) to attenuate noise. 1-2 kHz is the adjustable lower frequency (high pass filter) range, while notch filter setting is 50 Hz/60 Hz for noise elimination. This setting is mainly to attenuate the power line frequency. But this setting is not activated by default because of potential amplitude reduction and ringing. ADC converts the analog (i.e., EMG) signals to digital waveforms

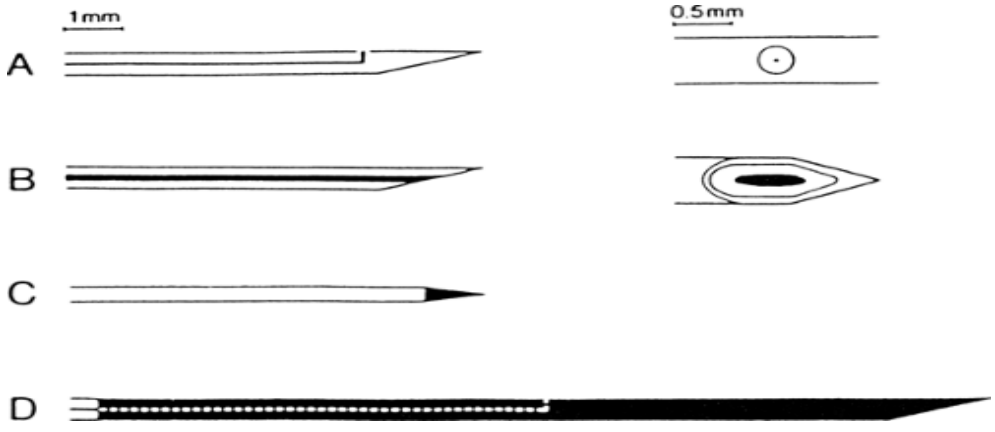

Fig. 2-3: Various EMG recording electrodes. A. Single fiber EMG electrode with one recording surface, B. Concentric needle electrode, C. Monopolar electrode and D. Macro electrode [110].

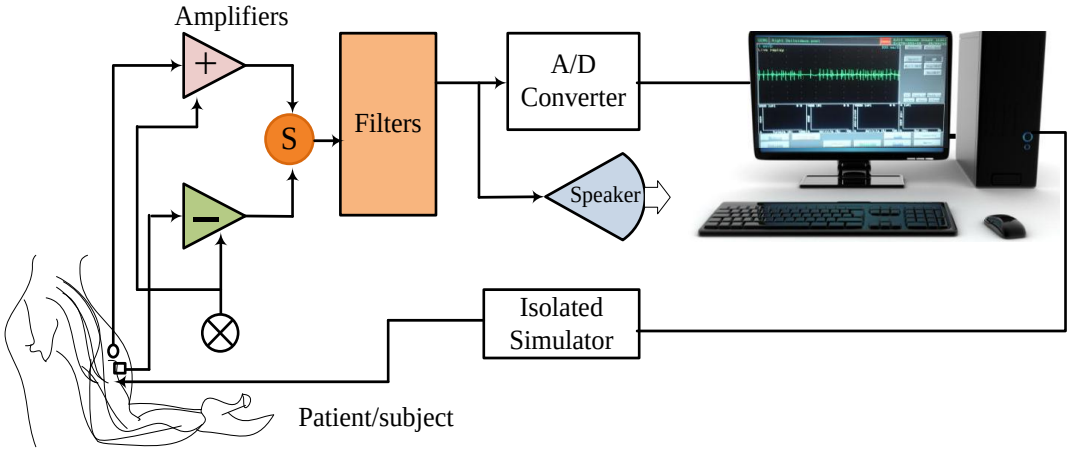

Fig. 2-4: Signal recording setup along with different processing steps. It includes amplifier, usually, instrumentation amplifier, filters (high pass and low pass filters), analog-to-digital converter (ADC), speaker, PC and Isoelectric stimulator.

along with displaying and storing waveforms in a digital format. It has an adequate sampling frequency capacity to prevent waveform distortion from the aliasing.

2.3.1.3 EMG machine

The neurophysiologist mainly concentrates on the assessment of MUPs in contracting muscle. EMG signal is recorded particularly in maximum voluntary contraction. With lower level of contraction, only a few MUs are activated and individual MUAPs can be identified. With increase in the force of contraction, more number of MUs start to fire yielding a complex superimposing pattern, termed as interference pattern (IP) EMG. As a result, individual MUAP identification becomes difficult. The integrity of the MUs composing the muscle relies either on the assessment of multiple MUAPs (atleast 20) obtained from various region of muscle or IP EMG using manual measurement protocol, which is a tedious task. Analysis of IP EMG is also useful to assess muscle activity, chronic muscle pain, disused muscle, muscle fatigue etc. and to diagnose disorders (See, Ch.1, Section 1.3.5). In practice, IP EMG is visually inspected with the help of the PC as well as listening the characteristics sound from the speaker as its bandwidth falls within human audioable frequency range. Such assessment is helpful only in severe abnormalities. However, in mild study, changes are not so pronounced and it often fails to come into the conclusion. In this contrast, quantitative methods with advanced signal processing and management procedure helpful for complete understanding of disease conditions.

In the final stage, the signal display unit has the sensitivity/gain control (to determine the potentials with range 1 μV-10 mV/division), sweep speed adjustment (0.1-500 ms/div) and adequate vertical/horizontal resolution on the monitor to enable visual assessment of waveforms. The oscilloscope or PC with sweep speeds of 510 ms/cm is used to characterize the MUs. However, slower speeds of 50 or 100 ms/cm are helpful

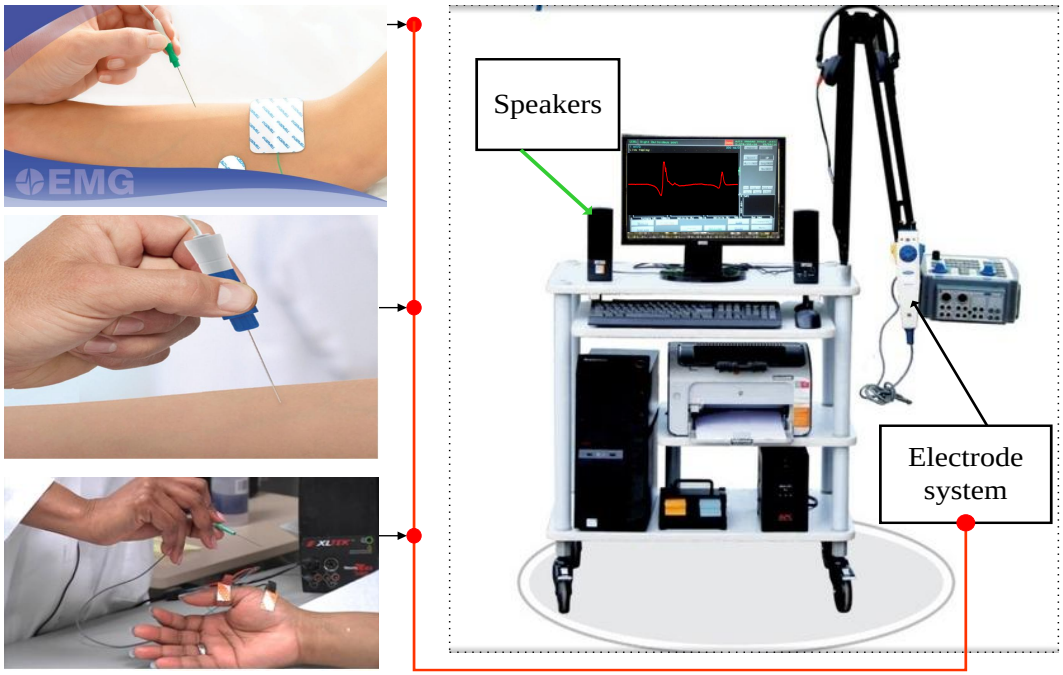

Fig. 2-5: NCV/EMG machine (*KEYPOINT®, Medtronic Functional Diagnostics*) and EMG recording strategies from various targeted sites [111].

to analyze the firing patterns. The most useful settings of in-built amplification is 50 μV/cm and 200 μV/cm for examining spontaneous and voluntary activities respectively. In usual routine study, the filter setting is approximately 30-10 kHz or more. The spontaneous activity is performed at resting position of muscle at a gain of 50 μV/div to assess abnormal spontaneous discharges which may be indicators of an underlying disease. By a small movement of the needle over the muscle, the insertional activities are obtained, which provide the electric response of muscle due to mechanical damages. Manual adjustment of cursors for measurements during EDX testing (i.e., NCS and EMG) and, free running and triggered modes (FRM and TM) are also in the display unit. The FRM updates the signal display continuously showing live signals. The TM helps recording the signals whenever a certain event (trigger) occurs to assess the signal variability and reproducibility. For MUAP analysis, a function of window triggering and delay line with adjustable delay time allows observation and analysis of signals preceding the trigger. It has the capability of trace raster/superimpose and square wave calibration signal to calibrate gain, sweep and other functions. In addition to that, in the final stage, along with the display unit, a high-quality audio amplifier and speaker with volume adjustment facility, are connected to produce characteristic sounds, for both potential recognition and criterion analysis [112]. Fig. 2-5 shows experimental setup and recording of EMG signals. SDMS allows to store real-time data without subjective inputs of subjects for further analysis, interpretation and research purpose. The clinicians usually provide analysis reports describing findings in linguistic forms or relevant parameter values with listed *normal reference* for final conclusions.

Table 2.1: Statistical and clinical information of two datasets that includes three categories subjects.

EMG dataset	Subjects and signal information	ALS	Myopathy	Normal
EMG_{N2001}	Subjects	8	7	10
	Male/Female	4/4	5/2	6/4
	Age range (Year)	35-67	19-63	21-37
	Mean age (Year)	52.8±11.8	36.3±14.6	27.7±4.5
	Recordings/Signals	50	50	150
EMG_{GNRC}	Subject	4	4	4
	Male/Female	3/1	2/2	2/2
	Age range (Year)	38-52	42-59	26-34
	Mean age (Year)	43.5±7	47.5± 7.8	29.3±3.4
	Recordings/Signals	20	20	20

2.4 Database

In order formulate and investigate feature fusion based-model performance, two real-time datasets are considered in this study. First dataset is collected from publically available online database [54] and second dataset is collected from Guwahati Neurological Research Centre (GNRC), Assam, India. The online dataset EMG_{N2001} (available at http://www.emglab.net/) was approved by the Institutional Review Board (IRB) of EMGLAB and local IRB for research practices. The second dataset EMG_{GNRC} was acquired using standard neurological protocol of GNRC hospital with proper guidance and was also approved by institute expert neurological committee. The datasets include three group of subjects-ALS, myopathy and normal as outlined in Table 2.1. However, none of the control subjects had signs or history of neuromuscular disorders.

Concentric needle electrode with a leading-off area of 0.07 mm^2 was used to record the signals by inserting into the muscle sites (i.e., Biceps brachii muscle, abductor pollicis brevis and tibialis anterior) with a surface ground electrode placed on the limb position. Furthermore to eliminate the unwanted needle movement, the amplifier cable (connected to the needle) was fixed to the muscle with a piece of tape. Under supervision, signals were collected at slight and constant level of contraction. Afterwards, signals were examined visually in computers and audibly with the aid of a speaker. The MUAPs that satisfied the triggering criteria were frozen on the computer screen for the measurement of amplitude as well as duration. Further, the MUAP potentials in repetitive measurements were examined to support whether a single MU gives rise to an MUAP or not. At a single recording site, a maximum of three different MUAPs was collected at an interval of 50 ms. Concurrently, the other monitor continuously displayed signal for the last half a second duration. When the tip of the needle was near to muscle fibers a characteristic crispy repetitive sound was heard. The recording was started for 11.2 s after confirmation of signal quality which was not too noisy and complex. To explore the whole muscle, care was taken to avoid recording the same MU.

Fig. 2-6: Signal recording during EDX test (i.e., NCS+EMG) and visualization of signals at GNRC hospital, (a)-(b). Signals were recorded from different subjects at various sites of muscle. Parameter settings in the equipment are shown in (c) (*Keypoint: Medtronic Functional Diagnostics, Skovlunde, Denmark*).

Following this procedure, nearly twenty signals were recorded for analysis.

Signals in EMG_{N2001} were filtered using in-built band-pass filter setting of 2-10 kHz and amplified with custom built-in-DISA15C01 of a gain of 4000 and sampled at the rate of 23437.5 Hz with DSP56ADC16 16 bit ADC. Each signal file in EMG_{N2001}, comprises of two data files-BIN File (.bin) and HEA File (.hea). BIN file consist of data samples of particular measurement and HEA File include various information of subjects (gender, diagnosis, age, disease duration, muscle site etc.). BIN files are later converted to readable format using MATLAB programs for visual investigation. However, EMGLAB can directly read the BIN file and displays the signals as if it behaves as online signal acquisition framework from subject with various adjustable facilities like filter setting, triggering, pausing etc.. Furthermore, characteristics sounds associated

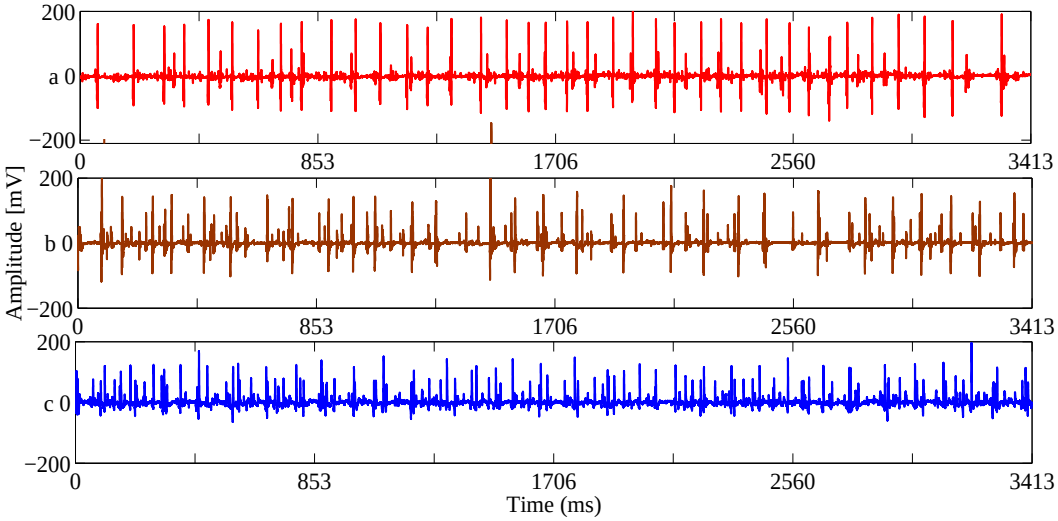

Fig. 2-7: Typical EMG patterns recorded in GNRC hospital at at a sampling rate of 23 kHz. (a) ALS, (b) myoapthy and (c) normal 4×10^4 samples. Here y-axis represents the amplitude of amplified signals with gain of 500.

with various signals can also be realized. Signals in EMG_{GNRC} acquired using in-built setup at sweep [ms/D]=20, sen [V/D]=50 μ and filter bandwidth of 20 Hz-10 kHz with same experimental procedure.

Although the frequency range of surface EMG signal is 0-1 kHz, excluding isoelectric components, its dominant energy concentrates in the range of 20-500 Hz [16]. Even in case of intramuscular EMG, this frequency range is more or less same [17]. So, signals of EMG_{N2001} and EMG_{GNRC} are again filtered using a twenty-order Kaiser window based filter with pass band frequency of 20-500 Hz which is different from that of in-built setup for acquisition of signals in EMG_{N2001}. It aims to narrow-down frequency band so as to acquire main signal components and to avoid unwanted components. In addition, a notch filter of 50/60 Hz is used to remove power line interference. Filtered signal are re-sampled to even number for ease of analysis. The signal recording during EDX analysis in GNRC hospital is shown in Fig. 2-6. Fig. 2-7 shows three typical EMG signals.

2.4.1 Study subjects

ALS is the relentlessly progressive neurodegenerative disease that affects the motor neuron of the motor cortex, brain stem and spinal cord. It finally leads to the loss of muscle mass, weakness and inability to control the movement or even death [55]. In ALS, the energy content of MUAP is higher and lower for myopathy in comparison to normal case. As a result, analysis of MUAP becomes essential both in clinical and off-clinical environments. Myopathy disorders is due to the lost of fibers which leads to muscle weakness [56]. Causes of various neuromuscular disorders change the anatomy

and physiology of MUs associated with muscle as shown in Fig. 1-2, which shows the changes due to disorders (See, b and c, Ch.1) in reference to that of normal (See, a, Ch.1). These reflect the significant changes in MUAPs and MUs of muscle through EMG signals [57]. Therefore, in typical clinical practice, a large number of MUAP is extensively analyzed visually for finding the types of disorder for effective treatment and supervision of subjects. However, in mild conditions, the changes often subtle for which subjective judgment becomes difficult.

In myopathy, MUAPs are of high-frequency contents, low amplitude, short duration and more complex than the normal MUAPs. Due to the loss of individual muscle fibers, the amplitude of MUAPs remain smaller and persist only for a shorter duration. As mentioned, in early and mild states, changes induced in the EMG (or MUAPs) signals often remain subtle that makes challenging the visual examination. Even in such case, the energy contents along with various well-defined quantitative parameters of MUAP or EMG provide significant information to characterize the signal and idea about pathology.

Important issue in this regard is that the number of MUAPs as well as the morphology significantly vary from signal to signal, even within same study group, which obstructs the extraction of all MUAPs from IP EMG. Furthermore, extraction of dominated MUAP based on morphological pattern is also difficult, specifically in mild state. In some case, say myogenic patients are characterized low amplitude MUAPs, typically less than 100 and sometimes very close to noise level which results poor SNR. On the other hand, in neurogenic patients, very high amplitude MUAPs (> 1000 μV) are observed. It is worth mentioning that the MUAP also depends on how close the tip of the needle to the muscle fibers. If the needle is very close to one or a few muscle fibers, then the MUAP will have a high amplitude and low rise time. Besides, due to various possible instrumental noises-needle, cables, amplifier, A/D-converter, baseline movements, the distant MUAPs have low amplitudes and long rise times. All of these factors complicate the analysis process.