APPLICATION OF ELECTROMYOGRAPHY IN MOVEMENT STUDIES

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The scope of this paper is to provide sound principles of EMG signal acquisition and processing in order to optimise the quality of signal and therefore lead to a better interpretation of mechanical muscle output during movement studies. Some background information will be provided on the origin of the EMG signal, factors affecting the quality of signal, recording techniques, signal processing, the fidelity and reproducibility of the signal, and few applications in movement studies. EMG has been a subject of laboratory research for decades. Only with recent technological developments in electronics and computers has surface EMG emerged from the laboratory as a subject of intense research in particularly movement studies, rehabilitation and occupational and sports medicine. Most of the applications of surface EMG are based on its use as a measure of activation timing of muscle, a measure of muscle contraction profile, a measure of muscle strength of contraction (physical load or psychological stress) or as a measure of muscle fatigue.

KEY WORDS: EMG, sports, movement studies, signal acquisition, processing

INTRODUCTION: The complexity of the biological system often introduces difficulties in the measurement and processing procedures. Unlike the physical systems, the biological system cannot be uncoupled like a subsystem that can be monitored and investigated individually. The signals produced by the system are influenced directly by the activity of the surrounding systems. The source of biological signals is the neural or muscular cell. These, however, do not function alone but in large groups. The accumulated effects of all active cells in the vicinity produce an electrical field which propagates in the volume conductor consisting of the various tissues of the body. The activity of a muscle can thus be indirectly measured by means of electrodes placed on the skin. The acquisition of this type of information is easy; electrodes can be conveniently placed on the skin. The information, however, is difficult to analyse. It is the result of all neural or muscular activity in unknown locations transmitted through an inhomogeneous medium. In spite of these difficulties, electrical signals monitored on the skin surface are of enormous clinical, physiological and kinesiological importance (Cohen, 1986). The electrical signal associated with the contraction of a muscle is called an electromyogram and the study of electromyograms is called electromyography (Winter, 1990). Electromyography (EMG) is a tool that can be very valuable in measuring skeletal muscle electrical output during physical activities. It is important that the EMG is detected correctly and interpreted in light of basic biomedical signal processing, and physiological and biomechanical principles (Soderberg, 1992). The usefulness of the EMG signal is greatly dependent on the ability to extract the information contained in it. EMG is an attractive tool because it gives easy access to physiological processes that cause the muscle to generate force and produce movement (De Luca, 1993a). Since the EMG tool is easy to use, it might be easily misused and the outcomes wrongly interpreted. Therefore, it is important to understand the principles of EMG signal detection and processing to optimise the quality of signal information.

The purpose of this paper is to provide sounded principles of EMG signal acquisition and processing in order to optimised the quality of signal and therefore leading to a better interpretation of mechanical muscle output during movement studies. In order to achieve this purpose, some background information will be provided on the origin of the EMG signal, factors affecting the quality of signal, recording techniques, signal processing, the fidelity and reproducibility of the signal, and a few applications in movement studies.

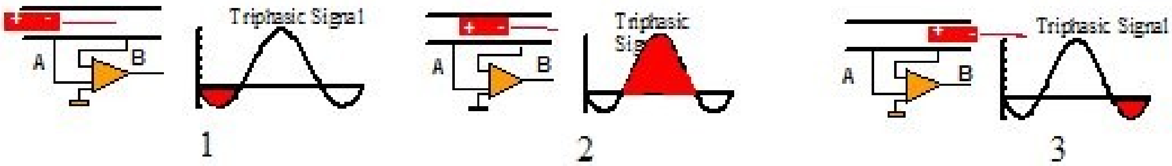

Figure 1 - Propagation of a Motor Unit Action Potential Waveform as it passes beneath the recording electrodes.

ORIGIN OF THE EMG SIGNAL: Muscle tissue conducts electrical potentials similarly to the way axons transmit action potentials. The muscle action potential (map) can be detected by electrodes in the muscle tissue or on the surface of the skin. Several events must occur before a contraction of muscle fibres. Central nervous system (CNS) activity initiates a depolarisation in the motoneuron. The depolarisation is conducted along the motoneuron to the muscle fibre's motor end plate. At the endplate, a chemical substance is released that diffuses across the synaptic gap and causes a depolarisation of the synaptic membrane. This phenomenon is called muscle action potential. The depolarisation of the membrane spreads along the muscle fibres producing a depolarisation wave that can be detected by recording electrodes (Figure1). In a two electrode system placed over the muscle site, the m.a.p. waveform is represented by a triphasic potential which is the difference in potential between pole A and pole B. Once an action potential reaches a muscle fibre, it propagates proximally and distally. A motor unit action potential (MUAP) is a spatio-temporal summation of MAP's for an entire MU. An EMG signal is the algebraic summation of many repetitive sequences of MUAP's for all active motor units in the vicinity of the recording electrodes. The order of MU recruitment is according to their sizes. The smaller ones are active first and the bigger ones are active last (Winter, 1990).

FACTORS AFFECTING THE QUALITY OF SIGNAL: Many factors may affect the quality of the EMG signal. They can be divided into physiological, physical, and electrical factors. Some factors are under the control of the investigator and some factors are not.

The physiological factors (such as the non-homogeneous medium between the muscle fibres - De la Barrera & Milner, 1994 - and the electrodes, the non-parallel geometry and non-uniform conduction velocity of the fibres, and the physical and physiological conditions of the muscle) over which the investigator has no control, contribute to the random component (noise) of the signal. While it is not possible to remove this random component completely from the measurement, the user must be aware of its presence and how to reduce its effects (Harba & Teng, 1999). Other physiological factors (such as the number of active MU, the MU firing rate, the fibre type, and the fibre diameter) which are also not under the control of the investigator contribute to the signal.

The physical factors are those that are associated with the electrode structure and its location on the surface of the skin over the muscle. These factors include the area and shape of the electrodes, the distance between the electrodes, the location of the electrode in relation with the motor points in the muscle, the orientation of the electrodes with respect to the muscle fibres, and the types of electrodes (active, surface or indwelling). The investigator can manipulate these factors to improve the quality of the signal.

The electrical factors are those that are related to the recording system which is used to collect the signal. The fidelity and signal-to-noise ratio of the signal is based on the quality of the recording unit. The following factors are important for obtaining a reliable signal with the highest signal-to-noise ratio. The differential amplification with a common mode rejection ratio (CMMRR) greater than 80 (Winter, 1990) or 90 (De Luca, 1993a) is used to eliminated noise coming from the power line sources. The CMMRR represents the quality of the differential amplifier. The input impedance of the order of 10^9 ohms (Winter, 1990) or 10^{12}

ohms (De Luca, 1993a) is recommended to prevent attenuation and distortion of the signal. According to Perreault, Hunter, & Kearney (1993), the skin preparation plays an importance role to reduce the impedance input and therefore diminish the signal distortion.

Finally, the frequency response of the differential amplifier is an important factor which insures that the signal is linearly amplified over its full frequency spectrum. The frequency response of the EMG signal is between 10 to 1000 Hz as proposed by Winter (1990). Table 1 shows the recommended minimum specification for surface amplifier. The spectrum of the frequency can be narrower and this will be shown later in the paper.

Table 1 Minimum Requirements for Surface EMG Amplifier

Variables	Minimal Requirements
Input Impedance	$>10^{10}$ at DC [a,b] $>10^{8}$ at 100Hz $>10^{6}$ [c] $>10^{12}$ [d]
CMMRR	>80 dB[a,b] >90 dB[c]
Amplifier Gain	200 – 10,000 [a,b,c]
Frequency Response	1 – 3000 Hz[a] 1 – 1000 Hz[b] 1 – 500 Hz[d]
Input bias current	< 50 mA [a]
Noise	< 5 μV RMS with a 100KΩ resistance[a]

a: Recommended by ISEK
b: Recommended by Winter (1990)
c: Recommended by De Luca (1993a)
d: Recommended by Lamontagne (1992)

RECORDING TECHNIQUES: A wide variety of electrodes are available to measure the electrical muscle output. Although microelectrodes and needle electrodes are available, they are not practical for movement studies (Soderberg, 1992). Surface electrodes (SE) (Németh, Kronberg, & Brostrom, 1990; Preece, Wimalaratna, Green, Churchill, & Morgan, 1994; De Luca, 1993b; Ferdjallah & Wertsch, 1998; Kwatny, 1970; McGill, Juker, & Kropf, 1996; Merletti, 1992) and Intramuscular wire electrodes (IWE) (Andersson, Nilsson, & Thorstensson, 1997; Arokoski et al., 1999; Davis, Krivickas, Maniar, Newandee, & Feinberg, 1998; Giroux & Lamontagne, 1990; Hagberg & Kvarnstrom, 1984; Kadaba, Wootten, Gainey, & Cochran, 1985; Moritani, Muro, & Kijima, 1985; Morris, Kemp, Lees, & Frostick, 1998; Park & Harris, 1996; Shiavi, 1974; Thorstensson, Carlson, Zomlefer, & Nilsson, 1982) are commonly used in movement studies. SEs are used mainly in a bipolar configuration along with a differential pre-amplifier to increase the signal. The differential preamplifier increases the amplitude of the difference signal between each of the detecting electrodes and the common ground. The advantage of the differential preamplifier is to improve the signal-to-noise ratio of the measurement. SE's are quick and relatively easy to use and have a fairly good reproducibility (Bilodeau, Arsenault, Gravel, & Bourbonnais, 1994; Elert, Karlsson, & Gerdle, 1998; Elfving, Németh, Arvidsson, & Lamontagne, 1999; Giroux & Lamontagne, 1990; Mathieu & Aubin, 1999; Sinderby, Lindstrom, & Grassino, 1995). SE's detect the average activity of superficial muscles, however, they do not selectively record single MU's (Basmajian & De Luca, 1985). MU's that lie superficially in a muscle contribute more to the signal than the deeper MU's. In surface EMG, electrode size and the interelectrode distance should be proportional to the muscle size. IWE are known to be more selective in MU detection than SE. This type of electrode has a small leadoff area lying between 25 μm and 100 μm, therefore detecting fewer MU's. The advantages offered by intramuscular electrodes are the following: they are much less painful than needle electrodes, they rarely interfere with

movement, they have a low sensitivity to movement artefacts (Notermans, 1984), and they can be easily implanted and withdrawn (Basmajian & De Luca, 1985). The active electrode which consists of placing the differential amplifier as close as possible from the recording electrodes. The active electrode reduces the noise from the cable motion (Hagemann, Luhede, & Luczak, 1985). Although, as reported by Nishimura, Tomita, & Horiuchi (1992), an active electrode was compared with a conventional one, and it was ascertained that the electrode could be replaced with the conventional one, and, moreover, it was preferable because it required less preparation time, and was less affected by environmental noise.
Of course an important question comes to mind: what should we use for kinesiological studies? This depends on the specific requirements for MU recording, reliability, reproducibility, and the interpretation of the muscle signal.

SIGNAL PROCESSING: As explained by Soderberg (1992), an analogy can be made between radio or television signals which are modulated, broadcasted and demodulated at the destination and the EMG signal which undergoes the similar process. The detected EMG signal represents a modulation of the alphamotoneuron pool command. The rate of MU firings is frequency modulated by the neural command. The summation of the frequency modulated MU action potentials produces an amplitude modulated envelope representative of the recruitment and firing rates of the original neural command. Demodulation refers to processing techniques that extract the information related to the neural command.
The demodulation techniques commonly used in the time-domain are: full-wave rectification, linear envelope (Chen, Shiavi, & Zhang, 1992; Kuster, Wood, Sakurai, & Blatter, 1994; Shiavi, Zhang, Limbird, & Edmondstone, 1992; Van Lent, 1994), integration of the full-wave rectification (Winter, 1990), and Root-Mean-Square Processing (Cook, 1992). The power spectral density (PSD) (Kwatny, 1970) is the function commonly used for frequency domain analysis of EMG signal. The parameters used from PSD are median (Sparto, Parnianpour, Reinsel, & Simon, 1997) and mean frequency (Davis et al., 1998; Elert et al., 1998; Kwatny, 1970) of the EMG signal. EMG signal processing will provide information on the activation timing of the muscle, to estimate the force produced by the muscle, or to obtain an index of the rate at which a muscle fatigues obtained from the power spectral density.

FIDELITY AND REPRODUCIBILITY OF THE SIGNAL: The usefulness of the EMG signal is greatly dependent on the ability to extract the information contained in it. Moritani et al. (1985) studied different electromechanical changes in the gastrocnemius and soleus muscles with simultaneous recordings using SE and IWE. Bipolar IWE were inserted in each muscle and SEs were placed over the muscular group. The results demonstrated that when there was either a decrease or no EMG signal from the gastrocnemius or soleus there was still surface EMG activation. This result is acceptable since the surface EMG is representative of the whole EMG activity of the muscular group. Then, when the EMG signal is very low or when the EMG signal of one muscle is evident and the EMG on the other muscle of the group is not, intramuscular wire electrodes are preferable over surface electrodes. Kadefors & Herberts (1977) suggested that surface electrodes be avoided because of the movement between muscle tissue and the surface of the skin and the risk of crosstalk from muscles around or near the investigated area. Giroux et al (1990) compared EMG surface electrodes (SE) and intramuscular wire electrodes (IWE) for isometric and dynamic contractions during a working task. Raw EMG signals from the middle deltoid, anterior deltoid and trapezius muscles were recorded by both IWE and SE for two conditions (isometric and dynamic contractions). Full-wave rectified and low-pass filtered EMG, and integrated EMG were processed from raw EMG signals. The statistical analysis performed on the integrated EMG was a factorial analysis model with repeated measures. Statistical results confirmed that EMG signals, from both SE and IWE, are reliable between trials on the same day. These statistical results also confirmed that SEs are more reliable than IWE on day-to-day investigations. Both electrodes recorded statistically similar signals, although the coefficient of variability between electrodes was very high (STDE%; 48% and 84%, for isometric and dynamic conditions respectively).

APPLICATIONS IN MOVEMENT STUDIES: Electromyography has been a subject of laboratory research for decades. Only with recent technological developments in electronics and computers has surface EMG emerged from the laboratory as a subject of intense research in particularly kinesiology, rehabilitation and occupational and sports medicine. Most of the applications of surface EMG are based on its use as a measure of activation timing of muscle, a measure of muscle contraction profile, a measure of muscle contraction strength (physical load or psychological stress), or as a measure of muscle fatigue.

Again the scope of this paper is not to present an exhaustive review of all various types of EMG applications but to expose a few sport and sport rehabilitation applications.

One of the important questions in SEMG consists of finding out the optimal sampling rate for dynamic contractions. If you must collect SEMG for long period of time or transmit the SEMG signal by telemetry, the sampling rate becomes an important issue, therefore the optimal sampling rate becomes an issue. Lamontagne et al. (1992) investigated the effects of different sampling rates on the power spectral density (PSD) and the integrated linear envelope (ILEEMG) of the raw surface EMG of the vastus lateralis during eccentric contractions at 60 degrees/s. The results revealed that raw EMG can be sampled at less than 500 Hz without significantly affecting the PSD and ILEEMG.

The following application illustrates the use of surface EMG as a measure of activation timing of muscle. Mâsse et al. (1992) investigated the pattern of propulsion for five male paraplegics in six seating positions. The positions consisted of a combination of three horizontal rear-wheel positions at two seating heights on a single-purpose-built racing wheelchair. At each trial, the propulsion technique of the subject was filmed at 50 Hz with a high-speed camera for one cycle, and the raw electromyographic signal of the biceps brachii, triceps brachii, pectoralis major, deltoid anterior, and deltoid posterior muscles were simultaneously recorded for three consecutive cycles. The EMG signals were processed to yield the linear envelope (LE EMG) and the integrated EMG (IEMG) of each muscle. The kinematic analysis revealed that the joint motions of the upper limbs were smoother for the Low positions-since they reached extension in a sequence (wrist, shoulder, and elbow), when compared to the High positions. Also, the elbow angular velocity slopes were found to be less abrupt for the Backward-Low positions. It was observed that in lowering the seat position, less IEMG was recorded and the degrees of contact were lengthened. Among the seat positions evaluated, the Backward-Low position had the lowest overall IEMG and the Middle-Low position had the lowest pushing frequency. It was found that a change in seat position caused more variation in the IEMG for the triceps brachii, pectoralis major, and the deltoid posterior.

This next application is a good example of surface EMG as a measure of muscle contraction profile. Németh, et al. (1997) studied six expert downhill skiers who had sustained anterior cruciate ligament injuries and had different degrees of knee instability. The electromyographic activity was recorded from lower extremity muscles during downhill skiing in a slalom course without and with a custom-made brace applied to the injured knee. Surface electrodes were used with an eight-channel telemetric electromyographic system to collect recordings from the vastus medialis, biceps femoris, semimembranosus, semitendanosus, and gastrocnemius medialis muscles from both legs. Without the brace, the electromyographic activity level of all muscles increased during knee flexion. The biceps femoris muscle was the most activated and reached 50% to 75% of the maximal peak amplitude. With the brace, the electromyographic activity increased in midphase during the upward push for the weight transfer and the peak activity occurred closer to knee flexion in midphase. Also, the uninjured knee was influenced by the brace on the injured leg, a decrease in electromyographic activity was seen during midphase. Spearman's rank correlation revealed a significant correlation between an increase in biceps femoris activity of the injured leg and increasing knee instability. We suggest that the brace caused an increased afferent input from the proprioceptors, resulting in an adaptation of motor control patterns secondarily modifying electromyographic activity and timing.

The surface EMG can also be used as measure of muscle fatigue and recovery. Tho, et al. (1997) investigated possible differences in muscle fatigue and recovery of knee flexor and

extensor muscles in patients with a deficient anterior cruciate ligament compared with patients with a normal anterior cruciate ligament. Surface electromyography of 15 patients with anterior cruciate ligament deficiency was performed while the muscles were under 80% of maximum isometric contraction, and after 1, 2, 3, and 5 minutes of rest. During the first 60 seconds of contraction, all muscles recorded significantly decreased mean power frequency and increased amplitude. The rate of decrease of mean power frequency was significantly greater in the injured quadriceps and normal hamstrings. All muscles except two recovered to the initial mean power frequency level after 1 minute of rest. All but two muscles in the injured and normal limb recorded an overshoot of mean power frequency during the recovery phase. This overshoot phenomenon also was seen for some muscles in the amplitude analysis. The findings confirm the fatigue state in all the muscles, suggest recruitment of more Type II fibres as the muscles fatigues, and show the physiological adaptation of the quadriceps and hamstrings to anterior cruciate ligament insufficiency. The current study indirectly shows dissociation between low intramuscular pH and mean power frequency during the recovery phase. It also indirectly suggests that the atrophied thigh muscles have fibre type composition similar to that of the normal side.
The intramuscular and surface EMG can be used as a measure of activation timing, and muscle contraction profile. Lafrenière CM et al. (1997) studied the intramuscular EMG of the lateral pterygoid muscles (LPM), surface EMG of the temporalis and masseter muscles and force measurements of the temporomandibular joint (TMJ) for subjects with internal derangement (ID) of the TMJ. The analysis of variance results of the integrated linear envelope (LE) EMG showed no significant differences between the two groups for the masseter and temporalis muscles. Therefore, there is no apparent reason to believe that these muscles are hyperactive in TMJ ID. The integrated LE EMG of the SLP was significantly lower in the TMJ group during molar clenching. The superior head of the lateral pterygoid muscle (SLP) seemed to have lost its disk stabilising function. The integrated LE EMG signals of the ILP were significantly higher in the TMJ ID group during rest, resisted protraction and incisor clenching. The ILP muscle has probably adapted to control the inner joint instability while continuing its own actions. The ILP muscle seemed to have lost its functional specificity. The results of the isometric forces showed that TMJ ID subjects exhibited significantly lower molar bite forces (297.1N over 419N, p=0.042) confirming that they have less muscle strength and tissue pain tolerance than subjects with healthy masticator muscle systems. A neuromuscular adaptation could be occurring in the TMJ ID masticator system affecting muscular actions and forces.

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Acknowledgements
The travel expense has been funded by The Natural Sciences and Engineering Research Council of Canada (NSERC). The author would like to thank Dr. Peter Stothart for his judicious comments on this paper.