In this article we will give you a rough overview of the applications of electromyography. We will explain what electromyography actually is, what the basic principles are and where, why and of course how it is used. Enjoy your reading and learning!

1. What is Electromyography (EMG)?

"Electromyography (EMG) is an experimental technique concerned with the development, recording and analysis of myoelectric signals. Myoelectric signals are formed by physiological variations in the state of muscle fiber membranes." (Basmajian, J.V. & De Luca, C.J., 1985).

In other words: EMG measures the electrical signals that initiate the muscle contraction. This allows a direct examination of the activity of individual muscles and has therefore found many applications in applied science:

Meidcal Research
Rehabilitation
Ergonomics
Sport Science

In general, three different parameters can be determined by electromyography:

1. Timing – when is a muscle activated?
2. Force – How strongly does a muscle contract?
3. Fatigue – Can a muscle call up its full power?

In biomechanics, surface electromyography (sEMG) has a special significance. In this method, electrical signals are measured by means of electrodes attached to the skin. In contrast to so-called intramuscular EMGs, in which the electrodes are stuck with a needle directly into the corresponding muscle, this has a great advantage: it is non-invasive. As a result, the subject can move much more freely. However, sEMG also has some disadvantages, but more about this and the three parameters later.

2. Basic Principles

As described above, we use EMG to record the electrical signal that initiates muscle contraction. This signal is the so-called action potential (AP), which is conducted from the nerve cells via motor end plates to the muscle. The size of the resulting depolarization zone is described in the literature as approximately 1-3mm². After the original excitation, this zone shifts as a Motor Unit Action Potential (MUAP) at a speed of 2-6 m/s along the muscle fibre. If an electrode is now placed above the muscle to be examined, depolarization and subsequent repolarization is measured in the form of a bipolar voltage change.

However, under normal conditions, it is extremely rare for a single motor unit (which consists of a motor end plate and one or more muscle fibers) to be innervated individually. This is because usually, several motor units "fire" and thereby cause the muscle to twitch. However, with electromyography you are not able to view and record all MUAPs in a differentiated manner and therefore, the signals are superimposed (Fig. 1). The resulting EMG signal is bipolar with a symmetrical distribution of positive and negative values, which means that the average value is zero. The amplitude of the sEMG signal is in a range from μV to low mV. Because of this low amplitude, it is necessary to amplify the signal by amplifiers with a range of 1000 to 10000. The energetic distribution of the EMG signal is essentially in the frequency range from 0 to 500 Hz, with the dominant components lying in the range 50-150 Hz.
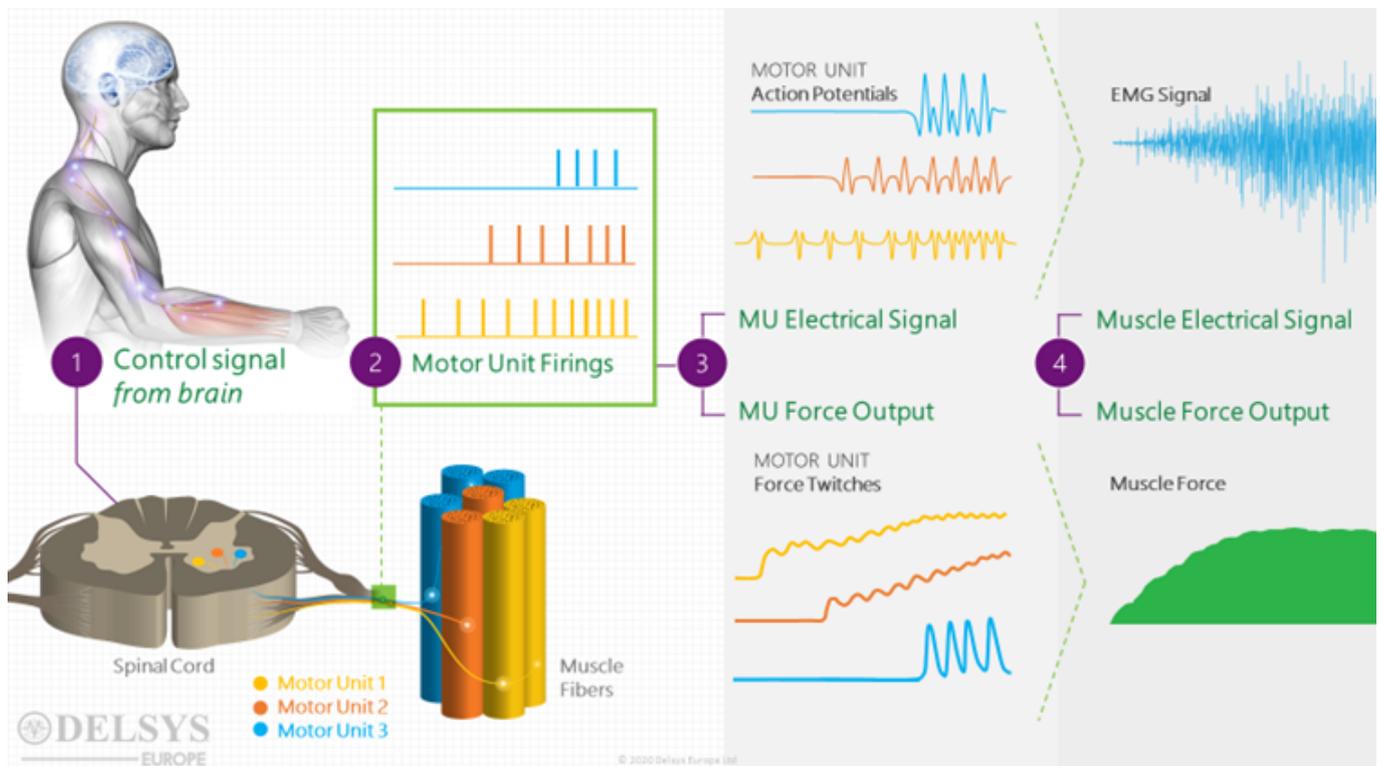
Figure 1: 1) The initial control signal to contract a muscle arrives from the brain in the spinal cord. 2) Signal gets transmitted to several motor units. 3) The signal arrives at the muscle and is transformed to a MUAP. The muscle contracts and produces a muscle force. 4) Superposition of individual MUAPs and their sum as the resulting EMG signal. The sum of MUAPs determines the total muscle force.

3. Influences on the sEMG signal and how to reduce them

As mentioned above, the use of surface electrodes not only has advantages but also several disadvantages. These are mainly influenced by factors that affect the appearance of the EMG signal and thus influence the later evaluation. It is not uncommon for so-called noise contamination or crosstalk from other muscles to occur. These disturbances of the EMG signal can have various sources, but can also be prevented or at least reduced with the help of the right technology or technique:

Physiological Noise
Ambient Noise
Baseline Noise
Movement Artifacts
Crosstalk from Other Muscles

Fatty Tissue
Relative Movement Between Skin and Muscle

In summary, the quality of the EMG signal depends on the sensor type, the quality and type of amplification, the sensor placement, and the electrode-skin interface. If you do not have a budget left in your lab to purchase the latest sEMG and amplifier technology, you will have to work with what you have available. However, you can still influence the last two points. These play a central role in the preparation of your measurements and have an enormous impact on the quality of your data.

4. Measurement Preperation

Now that you know what can affect your sEMG signal, we can start preparing for your sEMG measurement. In general, two questions should be answered: 1) Where and how do you attach the electrodes on your body? 2) How do I prepare the skin? Both questions should be answered with the primary motivation that we should try to keep the influences on the sEMG signal as low as possible to achieve the best possible quality of the signal.

Where and how to attach the electrodes on the body?

When attaching the electrodes, you should always try to hit the middle of the muscle belly if possible. This is important, because if you place the sensor too far on the edges, too close to the myotendinous junction or in the innervation zone (which are usually located in the muscle periphery, a separate article will be published soon for the exact localisation), the signal amplitude will be reduced. Placing the electrodes in the middle of the belly also reduces the crosstalk of other muscles to the desired sEMG signal. If the sensor is placed in the centre of the body and thus a large signal amplitude is obtained, the signal-to-noise ratio is also improved, since the amplitude of the noise is independent of the placement of the sensor.

As described above, you should always use two electrodes per sensor, so that the ambient noise is reduced to a minimum. These should be aligned along the muscle fibres so that the MUAPs reach one electrode first and then the other. It is important to pay attention to the

alignment of the muscle fibres and the pennation angle of the corresponding muscle. The distance between both electrodes should be kept as constant as possible (if not given by the sensor anyway). The amplitude of the sEMG signal is directly proportional to the interelectrode distance and the bandwidth is inversely proportional to the interelectrode distance. If this is not kept constant, the comparison between different muscles loses its validity. As described above, 10mm is a good compromise.

How do I prepare the skin?

The quality of the sEMG signal depends strongly on the conditions of the interface between skin and sensor. A preparation of the skin is essential. The aim is to minimize the resistance of the skin as much as possible in order to enable the sEMG signal to be picked up accurately (modern amplifiers are usually designed for skin impedance levels between 5 and 50 kOhm). In general, there are two points to consider when preparing the skin. The first is that you should remove all hairs from the area where the sensor is to be placed. Especially if the subject has a high sweat production or if you want to analyse highly dynamic movements, shaving prevents the electrodes from loosening. For hygienic reasons, it is best to use disposable shavers, which should be disposed of immediately after use.

The second point is to clean the skin. This involves removing dead skin cells that have a high resistance and cleaning the skin from dirt and sweat. In most cases it is sufficient to rub the skin lightly with a cloth soaked in pure alcohol. If this is not enough, you can use fine sandpaper to remove the upper skin cells (be careful not to hurt the subject). You can easily check whether this is necessary by measuring the resistance between the electrodes. You can do this, for example, by connecting the electrodes attached to the skin to a multimeter and setting it to measure resistance. The following table can be used as a rough orientation to estimate the values of the resistance:

Resistance (kOhm)	Recommendation
1 − 5	very good condition
5 − 10	good and recommended if feasible
10 − 30	acceptable for easy conditions
30 − 50	less good, attention is needed
> 50	should be avoided or requires a second cleaning run

Table 1: Recommendations for electrode/skin impedance ranges (Konrad, 2008)

To get an overall view of the signal quality, it is recommended to calculate and review the signal-to-noise ratio (SNR). This is calculated as follows:

$$SNR = \frac{sEMG\:Amplitude}{Baseline\:Noise\:Amplitude}$$

You can rate your calculated SNR value with the following table:

SNR	Recommendation
≥ 30	Excellent
10 − 30	Good
2 − 10	Acceptable
≤ 1	Unacceptable

Table 2: Recommendations for SNR ranges

If you are in an unacceptable range you should check again if you have eliminated all noise sources in the best possible way.

All set? Then the measurement can begin! What exactly you should measure clearly depends on the scientific question you want to answer. In the end, you always want to determine one or more of the three parameters mentioned at the beginning. For each of these parameters there are some points to consider in the study design. What these points are and how to evaluate the data afterwards can be found under data analysis.

5. Data collected and what now? - Postprocessing!

From the raw sEMG data we can already derive a rough overview of the contractions and

movements of the examined muscles (e.g. you can see when the amplitude increases and thus when a contraction took place, or how big different amplitudes are in comparison), but before we can perform accurate and standardized data analysis, we have to do some steps in postprocessing the data.

Tip: Make sure that you save the raw signal separately if possible, so that you can easily undo any errors and perform analyses of the raw signal!

1. Rectification

As described above, the raw EMG signal is bipolar with a symmetrical distribution of positive and negative voltage values. If you later want to compare different EMG bursts with each other, you cannot simply use the average value of all data points for the comparison, because this is zero. To enable a comparison, the first step is usually a rectification of the whole signal. To do this, one takes the magnitude of all measured data points so that all values are positive.
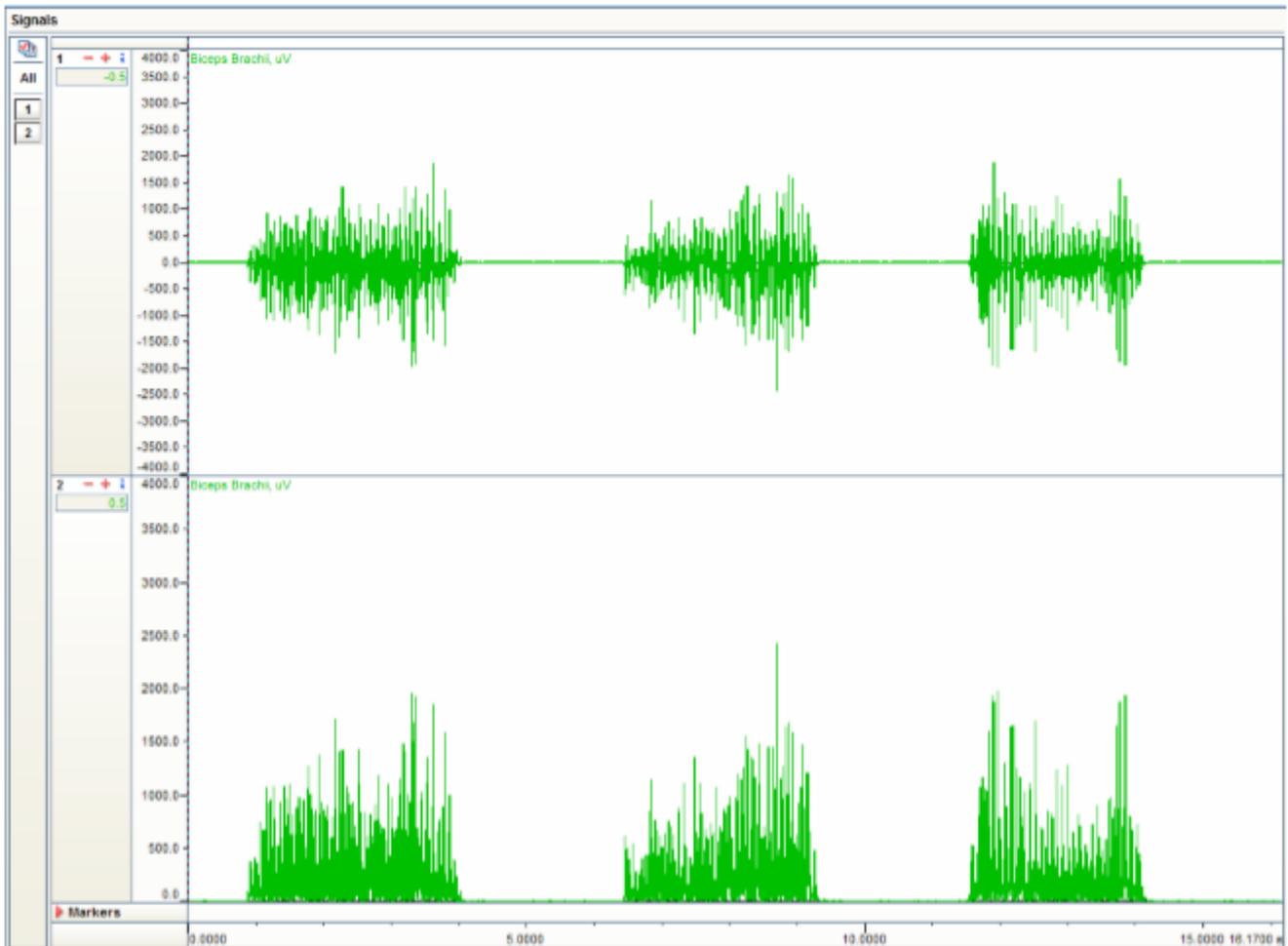
Figure 7: Top: Raw sEMG signal. Bottom: Rectified sEMG signal (Konrad, 2005.)

2. Smoothing

Due to the randomly overlapping MUAPs during muscle contraction, random interference patterns occur in the raw signal of the EMG, which is why deflections viewed individually cannot provide much information about the working of the muscles. In order to counteract this and increase the informative value, the EMG signal is smoothed. This is usually done by calculating the root mean squares (RMS) of the raw values for a specific time interval along the curve using the following algorithm:

$f_{rms} = \sqrt{\frac{1}{T_2-T1}\int_{T_1}^{T_2}[f(t)]^2\triangle t}$

This looks kinda messy but actually, the algorithm is easier than it looks at first glance. So, let us try splitting the formula: **F(t)** describes the raw sEMG signal. This signal is first squared and then the square root is drawn, which is the reason why the raw signal is rectified (as described in point 1). Unlike simple root mean squares (RMS) values, where you simply average all squared values and the square root gives you the result, you must proceed differently with continuous values like the sEMG. First, you should determine a time interval ($T_2 - T_1$), which in kinesiological studies is about 20ms (for fast movements) up to 500ms (slow or static movements). Now the values must be integrated over the considered range. This time window is now calculated for each value of the sEMG, which could look like this in practice:
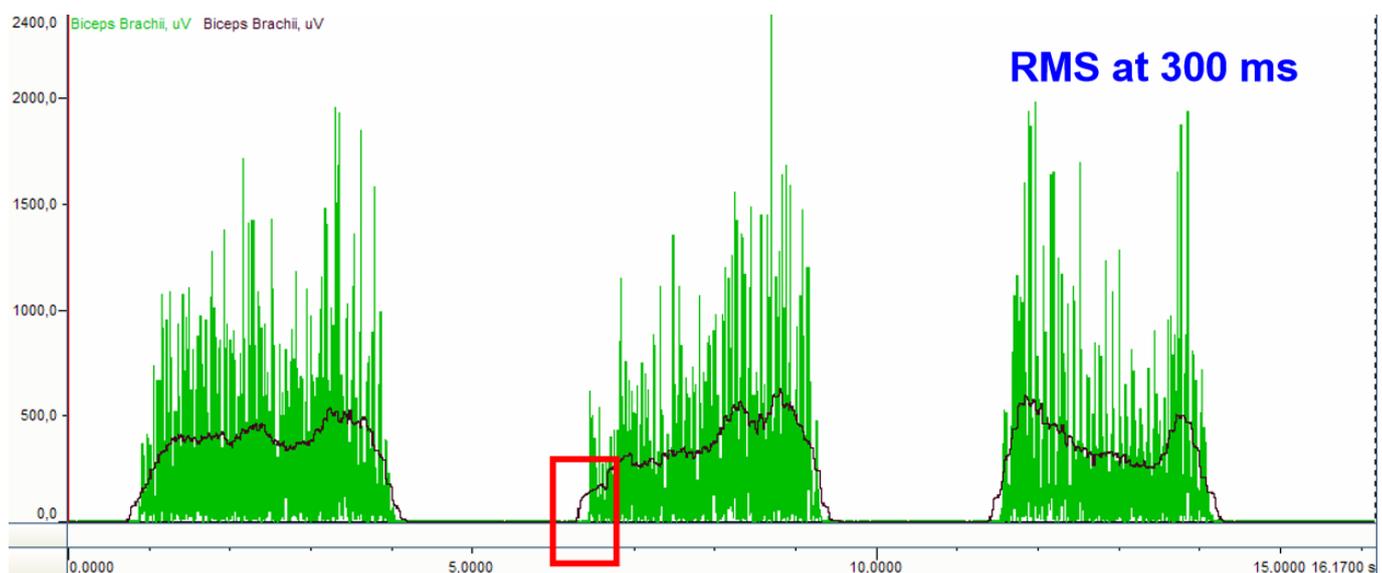

Figure 8: Rectified raw signal (green) and signal smoothed with RMS (black). The red box shows the danger of phase shifting if the time interval is too long. (Konrad, 2005)

The larger the time window you choose, the greater the risk that you misinterpret the timing of rapidly increasing sEMG signals as triggering the muscle too early (see red box).

But do not worry, with the help of software the RMS calculation is done in no time.

3. Filtering

As already described at the beginning, in the sEMG signal all frequencies in the range of 0-500Hz are superimposed, with the largest components in the range of 50-150Hz. The raw sEMG signal also contains all above-mentioned types of noise as shown in Figure 9 (in this figure, motion artifacts are shown).
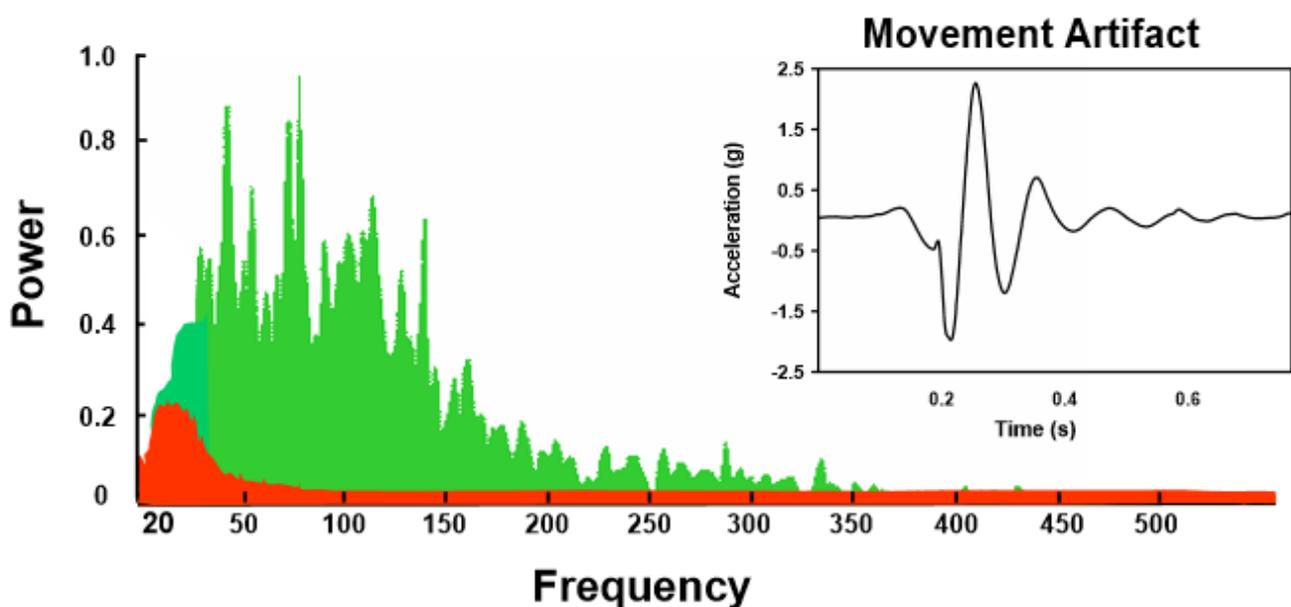

Figure 9: Green area: Frequency power spectrum of the sEMG signal of a relatively slight contraction (~10% of the maximum random contraction). Red area: frequency power spectrum of motion artifacts.

These have frequencies from 0 to far beyond those of the sEMG signal, with the main part being in the low frequency range (varying according to the type of noise, but not higher than 50Hz). Therefore, it makes sense to filter out some of the low frequencies and everything above 500Hz for later frequency analysis. This is done with a so-called bandpass filter (a mixture of high and low pass filter), which are usually already built into the amplifier. About what is the most suitable lower cut-off frequency, you can find various assumptions between 10 and 20Hz in the literature. Some argue that if the cut-off frequency is too high, too much of the sEMG signal is filtered out, which in turn affects the power spectrum of the signal (SENIAM). Others can prove that at 20Hz one can hardly filter out any more sEMG frequencies, but in return one can detect up to 10% less noise (Delsys, 2008).

In general, bandpass filters are the only type of filtering that should be performed. If your sEMG signal is disturbed for example by an ECG signal, one might think it would be a smart idea to analyse the ECG signal and filter the corresponding frequencies out of the EMG signal (so-called notch filters). But this is unfortunately a fallacy because this would delete too much of the EMG power.

6. Data Analysis

After you have minimized all influences on the sEMG signal, recorded and post-processed your data, it finally comes to the analysis and thus to the generation of actual, scientific results. As mentioned at the very beginning, there are three main parameters that can be derived from electromyography: Timing, force, and fatigue. Each parameter is derived differently from the sEMG signal and should therefore be described individually.

1. Timing

In general, the type of contraction is irrelevant to the analysis of the time at which a muscle is activated. Concentric, eccentric, isometric – it does not matter. The most important thing is that the recorded signal actually originates from the muscle that you want to examine (keyword: crosstalk from other muscles).

In order to determine exactly and in a standardised way when a muscle is being activated, a criterion must be defined on the basis of which the decision (muscle on or off?) can be made unambiguously. The simplest method is to record the background noise and determine the standard deviation. If the sEMG signal is now treated as a stochastic variable, 95% of the data points should be within two standard deviations. If this is exceeded for a certain period (usually 10 – 50ms), the muscle is recognized as activated. This method is also called the double threshold method since both, an amplitude threshold and a temporal threshold, must be exceeded. To record the background noise, after attaching the electrodes, ask your subject to relax completely before the actual measurement. This works best when he or she is lying down. One problem that can occur with this method is that you use very modern equipment, which means that almost no background noise can be detected in the sEMG

signal. A suitable alternative in this case is to set the amplitude threshold to a certain percentage (e.g. 5%) of the local maximum activation.

Due to the coordinative variability that occurs in any form of human motion, differences in the sEMG signal between cycles can be detected even in very standardized movements. Therefore, to describe a certain movement pattern by means of many repetitions, a uniform time frame is required. This is created with a temporal normalization. For this purpose, each cycle is divided into a fixed number of segments (e.g. 100) and the data points of each segment are averaged. This changes the X-axis scaling from a unit of time (seconds) to a percentage of the movement cycle (if you have selected 100 segments, each data point, i.e. average of each interval, corresponds to a 1% step). Now you can tell at what percent of the movement cycle the muscle examined is activated and when it is not.

2. Force

First, we can say: Yes, there is a relationship between sEMG signal, and the force produced in the muscle. But unfortunately, we must disappoint you, because this relation is not that clear at all. Since the sEMG signal is dependent on several variable parameters, there is (still) no concrete mathematical formula with which certain forces can be calculated from the sEMG signal (Fig. 10).

This relationship can be observed relatively easily: If the amplitude of the signal increases, the force generated in the muscle or the contraction speed also increases. This may be sufficient for qualitative analyses, but not for quantitative evaluations where we want to make very specific statements with exact numbers.

So how could we neutralize these influences and thus concretize the relationship between sEMG signal and force?

Again, the answer to this question lies in a normalization of the data. This time, however, in an amplitude normalization. The idea behind this is to recalibrate the sEMG signal to a physiologically relevant reference value. For this reference value, a maximum voluntary

contraction (MVC) is often used in practice. The sEMG data recorded in the actual measurement is then expressed as a percentage of the MVC. This does not externally change the shape of the sEMG curve, but only the Y-axis scaling. How MVC normalization should be performed, what the advantages and disadvantages are and what alternatives are available will be discussed in a separate article.
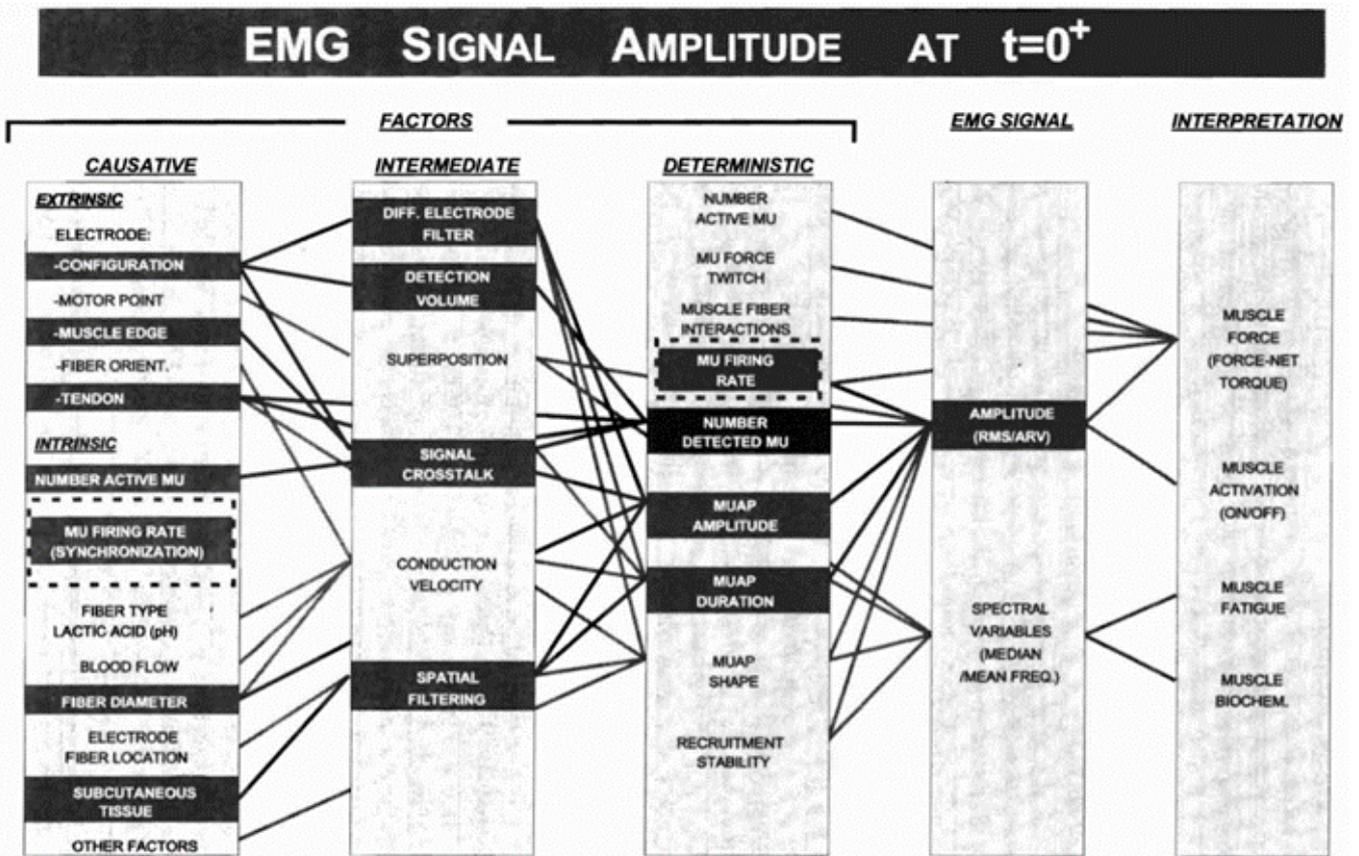

Figure 10: Relationships between the factors that influence the EMG signal amplitude at the beginning of a contraction (t = 0+). The time-dependent factors that will play a role during a sustained contraction are not shown (De Luca, 1997).

Once you have carried out such an amplitude normalization, it opens the possibility to investigate the relationship between sEMG signal and force between subjects or between individual measurements. However, another problem remains: The stability of the electrode position with respect to the active muscle fibres. Any change in this position can lead to a change in amplitude due to changes in tissue, spatio-temporal crosstalk of other muscles, and detection of motor units that have not been recorded before. Over the years, the

occurrence of this problem has led to isometric contractions becoming the most frequently investigated type of contraction, even though they are probably the least important in a kinesiological context. After all, isometric contractions do not lead to any form of movement.

In general, the sEMG-force relationship appears to be monotonically increasing with appropriate smoothing. The linearity, however, varies from muscle to muscle (Fig. 11) and is additionally dependent on the type of movement, the sensor's detection volume, training status and the muscle's state of fatigue.
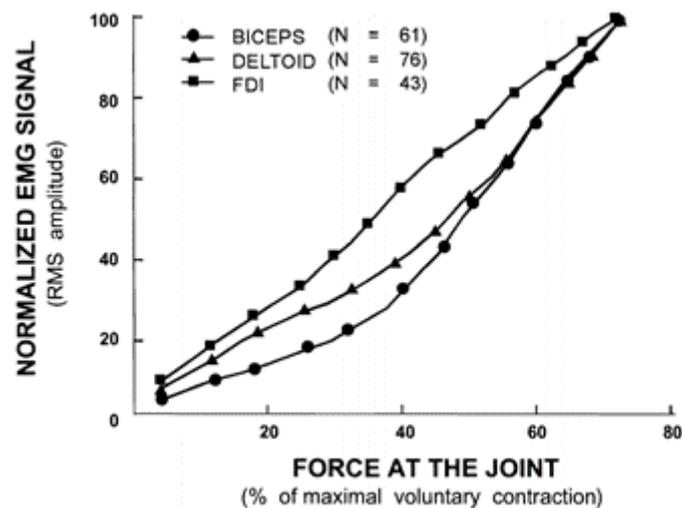

Figure 11: Normalized force/EMG signal relationship for three different muscles. The data have been greatly smoothed, with a window width of 2 s. Note the difference in linearity of the relationship among the muscles (De Luca, 1997).

If you want to show a sEMG-force correlation for non-isometric movements, you must limit your analysis to a period of measurement where the movement is nearly isometric. To do this, you should look for a fixed point in the corresponding movement and analyse only a minimal movement space around it.

Example: EMG analysis cycling

You want to investigate the connection between pedal force and the activity of the M.

Gastrocnemius. Let your subject perform an isometric MVC of the M. Gastrocnemius (after having placed the sensor correctly). Now let the subject cycle at different intensities, record the pedal forces and the sEMG signal. After recording, normalize the sEMG signal using the MVC values. For the analysis, select a certain crank position (e.g. 90°) and a movement range as small as possible (e.g. ± 1°). The smaller the range of motion, the closer the movement comes to an isometric movement and the less your result will be influenced. Now limit the signal for each crank revolution to the corresponding range of motion and determine the average value of each of these sections. Do the same for the recorded pedal forces. Now you can pair the normalized and averaged sEMG values with the averaged force values and plot them against each other. Voilà!

3. Fatigue

Fatigue of individual muscles is an important factor in biomechanical analyses. Without the help of EMG technology, a muscle is often classified as fatigued as soon as it can no longer maintain a certain contraction (this point in time is also called the point of failure). However, this approach implies that the fatigue occurs at a specific point in time, which is not correct. Muscular fatigue is a progressive process that can be examined by electromyography. For this purpose, we take a closer look at the frequency spectrum of the signal:

The raw sEMG can be seen as a result of the superposition of many different frequencies. In a simplified way, this is shown in figure 12 (on the left the superimposed signal and in the middle the three underlying frequency components). Using the Fast Fourier Transformation (FFT), the power distribution can now be determined and displayed as a frequency power spectrum. The amplitude part of each frequency component is determined and assigned to the respective frequency in a graph (Fig. 12 right). To describe the exact algorithm behind the FFT would go beyond the scope of this article. Fortunately, in today's world it is relatively easy to do this using software. Most analysis tools already have built-in functions that do the calculation for you (e.g. Matlab: Y = fft(X)).
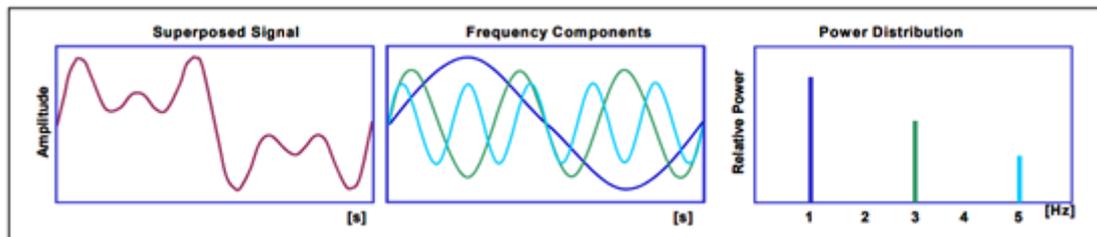
Figure 12: Model of a frequency dependent signal resolution based on FFT. The signal on the left side contains 3 underlying waves (Konrad, 2008)

If the frequency power spectrum of an sEMG signal is now calculated, the distribution curve would look something like Figure 13 (although not as smoothed as shown). From this spectrum, the four most important frequency parameters can be read: The mean frequency, the total power, the median frequency (which divides the area into two equal halves), and the peak power (the maximum value of the spectrum).
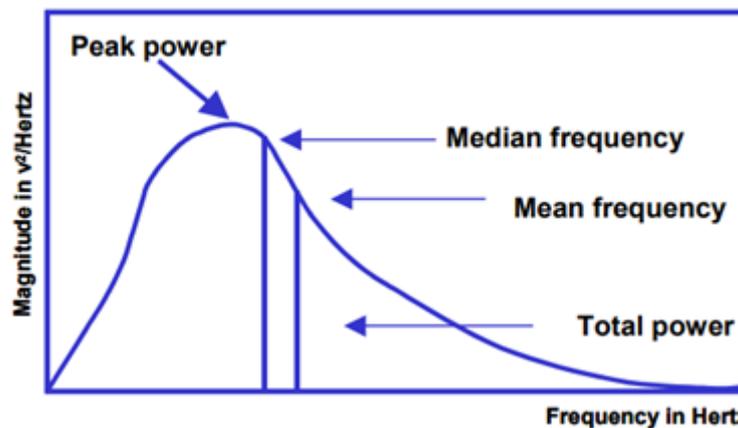

Figure 13: sEMG standard frequency parameters on the basis of FFT calculations (Konrad, 2008).

If your test person now performs a static, submaximal contraction, these frequency parameters will change as a function of time, which can be attributed to muscle fatigue: Due to the recruitment of motor units, the amplitude of the sEMG signal increases, whereas the mean or median frequency decreases over the contraction time (Fig. 14, top). This decrease in frequencies and the associated left shift in the power spectrum is in part due to a reduction in muscle fibre conduction velocity for the MUAPs. You can use the decrease in median (or middle) frequency as a non-invasive fatigue index by plotting it against contraction time as
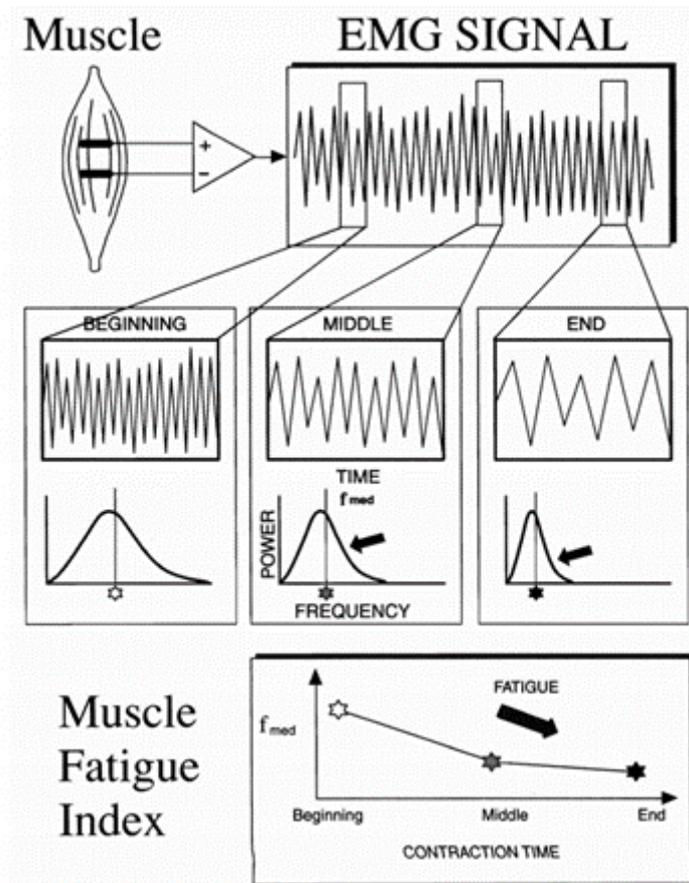
shown in Figure 14 (bottom).

Figure 14: Schematic explanation of the spectral modification that occurs in the EMG signal during sustained contractions. The muscle fatigue index is represented by the mean frequency of the spectrum (De Luca, 1997).

What information does a fatigue index give you?

In practice, there are two applications for investigating the fatigue effects of individual muscles. The first is the identification of muscular weaknesses that can lead to back pain, for

example. The second is the monitoring of strength training exercises, because short-term fatigue caused by training is a basic requirement for muscle growth.

In general, when doing fatigue tests, you should make sure that you use them during isometric contractions at constant submaximal strength (30 – 80% MVC) to avoid external influences. When comparing different test persons, you should definitely use the same electrodes and aim for the same sensor placement with regard to the innervation zone and tendon insertion. Also note the filter effects of the subcutaneous tissue.

7. Conclusion and Where You Can Find More Information

We hope that this article could give you a rough overview of electromyography. EMG is a huge subject area with a lot of applications, which is why we had to shorten this article in some places. Soon, more detailed articles on the individual topics of electromyography will appear here. Look forward to it!
However, if you want more detailed information and guidelines on sensor technology, sensor placement, data analysis, study design, modelling or even result presentation, we would like to give you two more addresses in addition to the literature that we used:

SENIAM

The SENIAM project (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) is a European concerted action in the Biomedical Health and Research Program (BIOMED II) of the European Union. It has resulted in European recommendations for sensors and sensor placement procedures and signal processing methods for SEMG, a set of simulation models for education and testing, a set of test signals, eight books, publications and a European network for SEMG: the SENIAM club.
http://www.seniam.org/

ISEK

The International Society of Electrophysiological Kinesiology (ISEK) is a multidisciplinary organization composed of members from health-related fields such as biomedical sciences as well as engineering, physical education, physical therapy, and many other disciplines. These clinicians and basic scientists are bound together by a common desire to study human movement and the neuromuscular system. Key topics in this discipline are analysis of large data sets for physiology, EMG modelling and signal processing, ergonomics, motor performance and sports science, motor units, movement disorders and rehabilitation technologies, multiscale and trans-scale approaches for movement and neurosciences, muscle physiology, neuromechanics, neural Engineering, and sensorimotor control.

https://isek.org/resources/

8. References

Konrad, P., 2006. The ABC of EMG: a practical introduction to kinesiological electromyography. Noraxon USA, Inc.
https://www.noraxon.com/wp-content/uploads/2014/12/ABC-EMG-ISBN.pdf

Luca, C.J. de, 1997. The Use of Surface Electromyography in Biomechanics. Journal of Applied Biomechanics 13, 135–163.
https://www.delucafoundation.org/download/bibliography/de-luca/078.pdf

Luca, C.J. de, 2008. A Practicum on the Use of sEMG Signals in Movement Sciences. Delsys Inc.
https://www.delsys.com/downloads/TUTORIAL/a-practicum-on-the-use-of-semg-signals-in-movement-sciences.pdf

Wang, J., Tang, L., E Bronlund, J., 2013. Surface EMG Signal Amplification and Filtering. International Journal of Computer Applications 82, 15–22.
https://pdfs.semanticscholar.org/c348/f06416aa03154c40bb82d5b26cef40e5840d.pdf