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A Critical Review and Proposed Improvement in the Assessment of Muscle Interactions Using Surface EMG

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1. Introduction

The purpose of this chapter is to propose a mathematical relationship between EMG excitation recorded from muscles in opposition to, or in coordination with each other. The concept of correlating co-activation between muscles with EMG parameters is not new. Cowan et al. (1998) investigated the use of the Pearson Product-Moment correlation coefficient to quantify muscle co-activation using electromyography. They concluded that this method shows promise for describing side differences in diplegics and for assessing the effects of physical therapy and other interventions. Careful reading of this work shows that only "select" intervals of the EMG data were compared. These intervals were selected on the basis of "burst activity" of one muscle. This selection is done by hand and for large quantities of data, typical of a gait laboratory, would be labor intensive. In our laboratory the authors have found the Pearson Product-Moment unable to distinguish between two noisy signals from inactive muscles and two that are fully active. Using insights from the literature review, presented below, this chapter will propose an alternative, continuous function for describing muscle interaction over any and all portions of a gait cycle.

2. Background

The history of the development of EMG's as an assessment tool follows closely the development of mathematics over the last century and a half. In an extensive review, Reaz et al.(2006) traces this history from Francesco Redi's documentation of electrical activity in a muscle in 1666, to its present use as a controlling mechanism for modern human computer interaction. Most of the mathematical analysis applied to EMG signals concerns itself with the relationship between various parameters of the signal and the forces generated in the muscle.
In its simplest form, an isometric contraction results in electrical activity in the muscle. De Luca (1997) states that while a simple equation describing this relationship would be extremely useful, such a simple relationship does not exist. In spite of this, numerous researchers have applied a countless variety of methods to the extraction of force from EMG signals.
Christensen et. al. (1986) compared the number of zero crossings with force production and found a linear relationship up to 50% of a maximum voluntary contraction. At low levels of maximum contraction the number of spikes was found to increase with increasing force

(Haas, 1926). At higher force levels, the mean rectified value of the signal was found to exhibit linearity with force (Fuglsang-Frederiksen, 1981). Other investigators turned to the frequency domain and demonstrated an inverse relationship between force and frequency (Ronager et al, 1989). At the same time it has been shown that mean power frequency increases with increasing force (Li & Sakamoto, 1996). A study in 1999 showed that the median frequency increases with force up to a point equal to 50% of the maximum contraction (Bernardi M, et al. 1999). In a review article on surface EMG and muscle force, Disselhorst-Klug, et al. (2009) conclude that muscle force can be estimated from EMG signals in geometrically well-defined situations during isometric contractions.

When limb motion and coordination are involved the relationship between (dynamic) EMG and force takes on greater dimensions of complexity. There are three basic types of data utilization involved in the study of dynamic EMG. Most common is the interest in the presence or absence of the particular muscle's activity during a portion of some movement, for example a gait cycle. A second interest is in the envelope shape of the EMG waveform over an entire movement. Lastly, there is the interest in relating the force generated by a muscle to itself (at some other part of the movement) or to some other muscle (Rechtien, et al. 1999). In order for the EMG representation of forces to be related to one another, each must be normalized to some standard value.

Burden (2002) gives an extensive review of research, performed over the last two and a half decades, on normalization methods. The author identifies eight methods of normalization. Of these eight, two are of the most interest: first, a method whereby an EMG signal is divided by the maximum of itself (Peak Task, PT), and a second (Mean Task, MT) whereby an EMG signal is divided by the mean of itself. The author reports that, with respect to other more complex methods, both the PT and the MT methods reduced inter-individual variability, and improves the sensitivity of surface electromyography as a diagnostic gait analysis tool. The use of these methods also increases the effect size and hence the power of statistical comparisons between groups in relation to the output from other methods. The drawbacks of these methods are, first in the case of PT, the selected maxima could easily be an artifact in the recording of the signal. In the second method, normalizing to the mean of the signal could easily result in the existence of normalized EMG points in excess of 100%. If these points are attenuated to 1.00 as is often the case, the normalized task EMGs may not reveal the proportion of an individual's muscle activation capacity required to perform a specific task.

To compare EMG patterns between muscles groups, it is necessary to use a time-normalization technique so that a point-by-point comparison of EMG activity is possible. Carollo JJ & Matthews (2002) suggest that this can be done by breaking the EMG pattern up into individual stride cycles, which are considered the period between successive heel-strikes in the same leg. The individual EMG stride patterns are then time normalized, expressed as a percentage of total cycle. In a review paper on muscle coordination, (Hug, 2011) finds fault with this method because of the variability of the point of toe-off (between 58 and 63% of the gait cycle). To correct this, Sadeghi et al. (2000) and Decker et al. (2007) use "curve registration" or "Procrustes analysis" methods, respectively. Curve registration relies on finding the peak points in the joint power curves and aligning gait cycles accordingly. The Procrustes method describes curve shape and shape change in a mathematical and statistical framework, independent of time and size factors. Thus the method normalizes both time and stride magnitude at the same time.

Hodges & Bui (1996) state that, in order to allow comparisons between muscles, experimental conditions and subjects or subject groups, accuracy of onset determination is crucial. Onset is most often recognized as the point where the EMG values cross and remain above a pre-chosen threshold value. The choice of this threshold value varies among researchers. Some place it at two standard deviations above the noise level (Micera et al. 1998). Lidierth (1986) added to this method by specifying that the threshold value be exceeded, and remain so, for a specific time constant. Others use a percentage of the peak EMG, and report that this percentage varies from 15 to 25% of the maximum signal (Staude, 2001). More sophisticated methods evaluate statistical properties of the measured EMG signal before and after a possible change in excitation level (Staude & Wolf, 1999).

De Luca (1997) suggests that, at least in the case of the threshold method, off time be found as the opposite of on time, that is when the amplitude falls below the same percentage of maximal contraction. He further suggests that when comparing on and off times of two muscles, that a 10ms window of error is the best that can be expected.

Having extracted a measure of force from the EMG signal by whatever means, and knowing when a muscle is active or inactive, attention turns toward the comparison of activity in two or more groups of muscles. The most elementary technique for the examination of two coordinating muscles groups is the visual inspection of the raw EMG signal together with appropriate graphics of the joint angles. Conclusions drawn from such observations are subjective at best, thus a more quantitative method is needed (Kleissen et al. 1998).

De Luca (1997) defines two parameters that are commonly used to represent the EMG signal: the average rectified value and the root mean square value:

$$\mathrm{RMS} = 1/n\sum x^2(i)$$

Here x is a sample point with the sum taken over sample size n.

For comparison purposes Fukuda et al.(2010) state that the RMS value is prefered because it is a parameter that better reflects the levels of muscle activity at rest and during contraction, and for this reason, it is one of the most widely used in scientific studies. A slightly more complex method of analysis was reviewed by Fuglsang-Frederiksen (2000). When comparing the activation of different muscles, he found that the turns/amplitude analysis method was more useful than other methods. Turns analysis consists of counting the number of positive and negative potential changes exceeding 100υv ("turns") and their amplitudes. The turns ratio is computed by dividing the mean amplitude (of the turns) by the number of turns. The method was used by Garcia et al.(1980) as a quantitative assessment of the degree of involvement of antagonist muscles.

In a variation on the turns counting method, Jeleń & Sławińska (1996) compared the activation of two muscles using a spike counting method. This method counts the number of times the EMG signal crosses a "noise level" threshold. These authors showed that this count is in good agreement with muscle activity.

Area under the EMG curve has been used successfully to compare co-contraction. In a unique normalization scheme, reported by Poon & Hui-Chan (2009), EMG co-contraction ratios were calculated as ratios of the antagonist EMG area to the total agonist-plus-antagonist EMG areas. The authors claim this technique allowed the comparison of data obtained on different days for within- or between-subjects.

Work presented in the next section will demonstrate that the method to be outlined in this chapter is quite similar to Poon's (Poon & Hui-Chan, 2009). However a simple mathematical construct reveals that the author's ratio is not unique:

$$A/(A + a) = B/(B + b)$$

$$\text{Let: } B = 2 * A \quad \text{and} \quad b = 2 * a$$

If "A" in the above equation is antagonist EMG area and "a" is agonist area, it is possible to conceive of another muscle group such that antagonist area "B" is twice that of "A" and agonist muscle "b" is twice the area of "a". The calculation for both muscles groups will produce the same co-contraction ratio, however a clinician, observing the muscle group's behavior, would find the two levels of co-contraction to be quite different. The authors of this chapter will assert that it is not possible to represent the co-activation of two muscles by a single parameter. One must consider the activation of both relative to the normalized value and the ratio of each to the other.

The next level of sophistication in the analysis of EMG data is the examination of the frequency content of the signal. Several parameters are obtained from the power spectrum (the Fourier transformation of the EMG signal). The mean frequency is defined as the mathematical mean of the spectrum curve, the total power is the integral under the spectrum curve, and the median frequency is defined as the parameter that divides the total power area into two equal parts. Finally the peak power is the maximum value of the total power spectrum curve.

The most commonly used parameter in the frequency domain is the median frequency. Hermens et al.(1992) report that this parameter deviates from its normal value in a number of neuromuscular disorders, therefore the parameter is often used in clinical settings. In a comparative study this parameter, like the turns ratio and the spike count, would be calculated for each muscle group and then compared using a statistic such as the ANOVA or a paired t-test (Lam, 2005). A slight variation on this is the mean power frequency which is found by dividing the summed product of the frequency and power by the summed power. Feltham et al. (2010) used this parameter to demonstrate differences in co-contraction levels between the right and left sides in children with spastic hemiparetic cerebral palsy and both arms of typically developing children. In the case of the other two variables peak power has been shown to be related to muscle fiber conduction velocity and total power to muscle force (Li & Sakamoto, 1996; Farina et al. 2004).

Among the newest methods of EMG analysis are those involving wavelet analysis, which examines both the frequency and time domain combined. A wavelet transform is a Fourier transform performed on a particular section of an EMG signal. Further, the time width (or window) of the “section” can be dependent on the frequency content of that section. That is, the window is narrowed for high frequencies and widened for low frequencies. Karlsson et al.(2009) define this as a mathematical microscope in which different parts of the signal can be observed by adjusting the focus. When testing children with cerebral palsy, Prosser et al.(2010) point out that wavelet analysis eliminates the need for amplitude normalizations. This is beneficial because many of these subjects cannot make a maximal contraction.

In a paper presented at the IEEE conference on Engineering in Medicine and Biology Dantas, et al.(2010) compared Fourier analysis with wavelet transform analysis. They point out that Fourier analysis assumes signal stationarity, which is unlikely during dynamic contractions. Wavelet based methods of signal analysis do not assume stationarity and may be more appropriate for joint time-frequency domain analysis.

The nature of the Fourier analysis is that it transforms the signal into a series of sine-cosine functions and is therefore especially well adapted for analyzing periodic signals. Herein lies its major drawback, EMG signals are not only non-stationary, but non-periodic, “fractal” and seemingly chaotic. Borg (2000) points out, that instead of decomposing and

reconstructing a signal in terms of the sines and cosines functions, wavelet analysis allows the use of an array of waveforms such as: saw tooth functions, rectangle waves (Walsh functions), or finite time pulses. In a paper published last year, Bentelas (2010) demonstrated how the Continuous Wavelet Transform (CWT) is mathematically similar to surface EMG signals with noise and is therefore the favorite candidate for analyzing these signals.
The wavelet transform method has been applied with increasing success. In a paper on the ergonomics of driving, Moshou et al. (2000) clearly demonstrate the ability to remove noise from the EMG signal. As a result, small coordinated muscle activity of the shoulder can be observed, that would otherwise have been hidden in the noise. The use of this method to investigate dynamic muscle dysfunction in children with cerebral palsy has lead to clear distinctions between this population and the normally developing group (Wakeling et al. 2007). Lauer et al. (2007) expanded on this and were able to show differences in levels of co-contraction between the less and more involved side.

3. Methodology

With the above review in mind, the authors propose a method of comparing two EMG signals. While most of the illustrations presented will be of raw or stylized raw EMG data, the method will be demonstrated to work equally as well on filtered, enveloped data. The method begins with a full wave rectification of surface EMGs recorded as gait data. The gait data presented here will be from multiple walks; each walk will have been cut into cycles beginning and ending either at toe-off or heel-strike and then pieced together end to end (i.e. toe-off to toe-off or heel-strike to heel-strike). For simplified illustrative purposes only one cycle will be presented, however all mean values will have been calculated over the entire ensemble.
The method of normalization is a combination of both the "Peak Task" and "Mean Task" methods of (Burden, 2002). Figure 1, below, is an illustration of the method. For illustrative purposes a stylized EMG signal is presented. The signal consists of two sine waves, of different

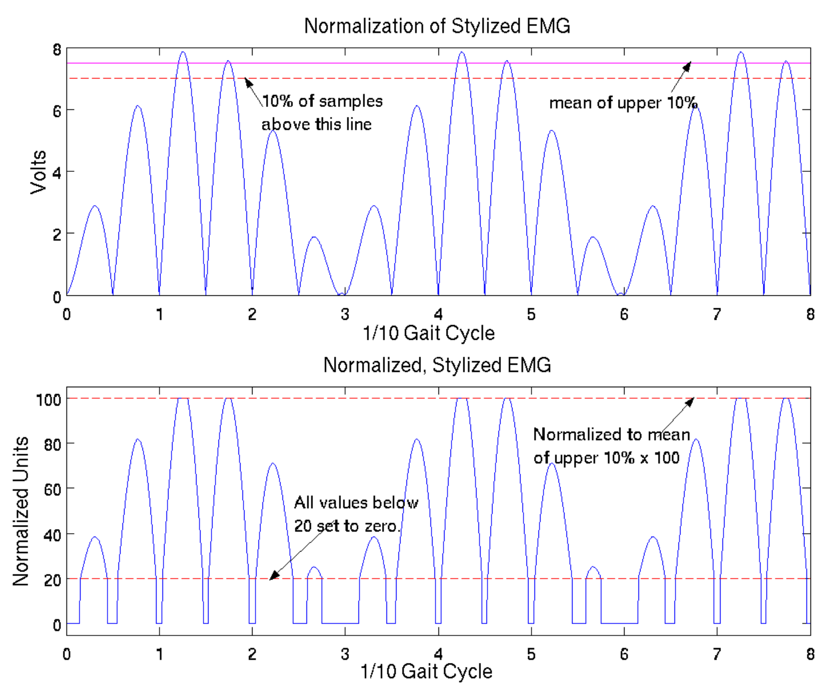
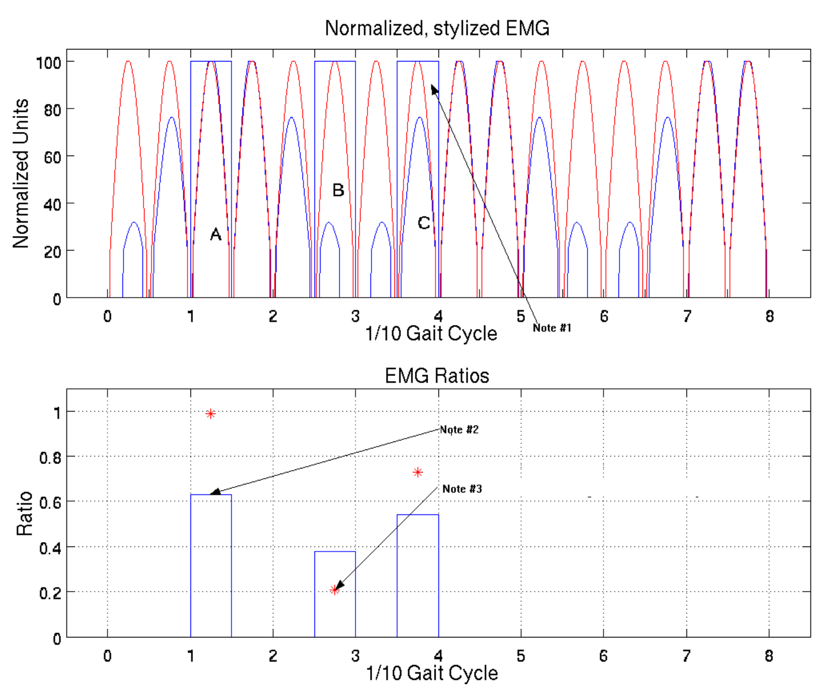


Fig. 1. Normalization method stylized EMG data constructed from several sin waves is used to demonstrate a method of normalization.

amplitude and frequency summed together. The timing of half a "wave" will be considered one tenth of a gait cycle. For the normalization process, a set of points are found such that they are the upper 1/10 of all samples in the particular gait cycles of interest. The mean of these samples (in the illustrative case 80 points are found to have a mean of 7.8 volts) is taken as the normalizing value. All points in the ensemble are then divided by this mean. The result of this division will be a signal with several points that have a value higher than unity. These will be considered artifacts and set to the value one. The signal is then multiplied by 100. After this multiplication, all values below 20 are considered to be noise and are set to zero.

The comparison of two muscle excitations requires the defining of two parameters. The first of these parameters will be called the "Excitation Index". If it can be imagined for a moment that, for a tenth of a gait cycle, the EMG were at maximum potential, the signal over that time period would be a full ten volts. The normalized value would be 100 over the entire time period (tp). The integration of this full excitation would equal the area of a rectangle (100 x tp). When two signals are involved, both maximally on for the same time period (tp), the total possible area under both signals is (200 x tp). This will be considered the "standard" Excitation. The excitation index will be defined as the sum of the integration of the two EMG signals over a tenth of a gait cycle divided by that tenth's "standard". It should be noted here, that tp is not a constant and is likely to vary over each gait cycle, as a result a "Standard Excitation" must be calculated for each tenth cycle.

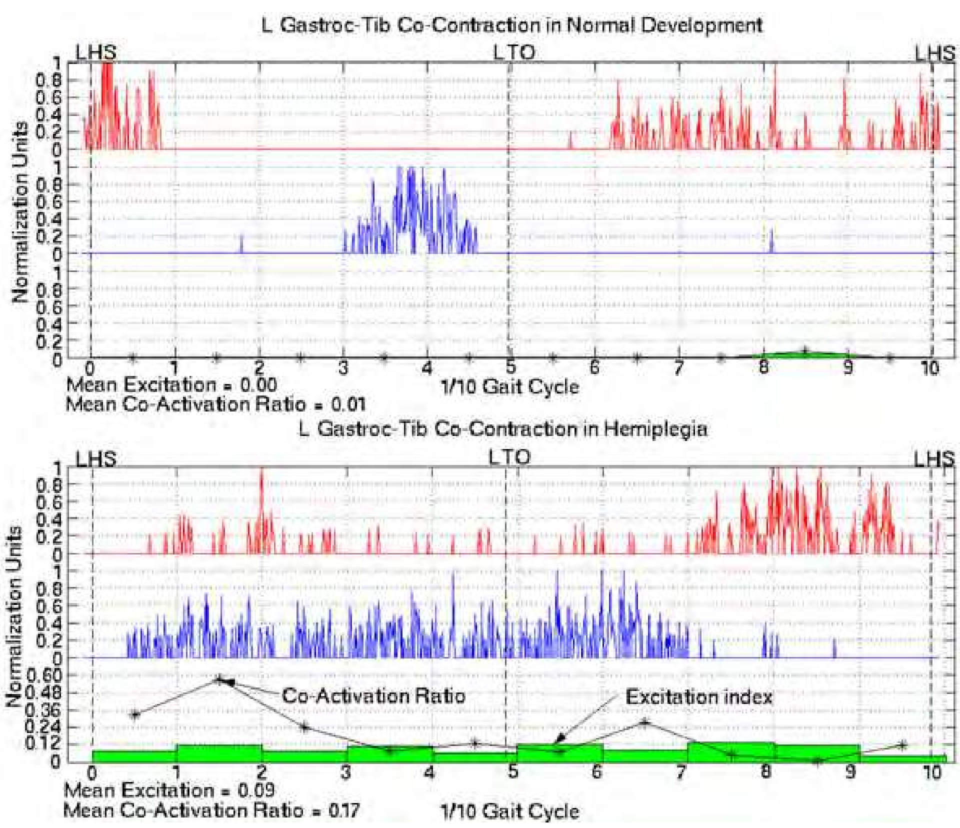
The second parameter to be defined will be called the co-activation ratio. This ratio will be defined simply as the smaller of the two integrated EMG signals divided by the larger. The result will always be a number between zero and one. An illustration of the calculation of the two parameters is presented in figure 2. In this case the second EMG signal is



Note:
#1 Area under the rectangle equals the total area of a 1/10 gait cycle. Twice this area is the maximum integral of the combined EMG signals (The Standard Excitation (SE)).
#2 Bar Height = The ratio of the sum of the integral of both EMG signals / SE.
#3 Point Value = Ratio of the two "stylized" EMG signals in "B" above.

Fig. 2. Stylized assessment method

represented as a full wave rectified sine wave whose frequency was set to the combined frequency of the first. In the case of the A'th tenth cycle both EMG signals are almost the same, however the area of a sin wave is not equal to a square wave. The height of the bars of the graph in the lower half of the figure represents this difference in area. In the case of "A" the area under the two stylized EMG signals is 0.6 of 60% of the "Standard Excitation". The red dot represents the ratio of the two signals, slightly less than one because the two areas are almost equal. The B'th and C'th tenths can be similarly interpreted. The assessment system can be applied to the co-activation of two antagonistic muscles (better known as co-contraction) as shown in figure 3. This figure delineates the differences between co-contraction in a normally developing limb and one with hemiplegia. Clearly, in this gait cycle, there is almost no co-contraction evidenced in the normally developing subject. This is not the case in the subject with hemiplegia. A quick review of the profiles reveals that, while the highest co-contraction occurs in the eight tenth of the gait cycle, the total excitation of both muscles is less than 10% of maximum. From the mean values it can be seen that, while the excitation index is just below 9%, the co-activation ratio is just below 17% (the rounded off value). With these values presented, it is left to the clinician to decide if this co-activation is significant.

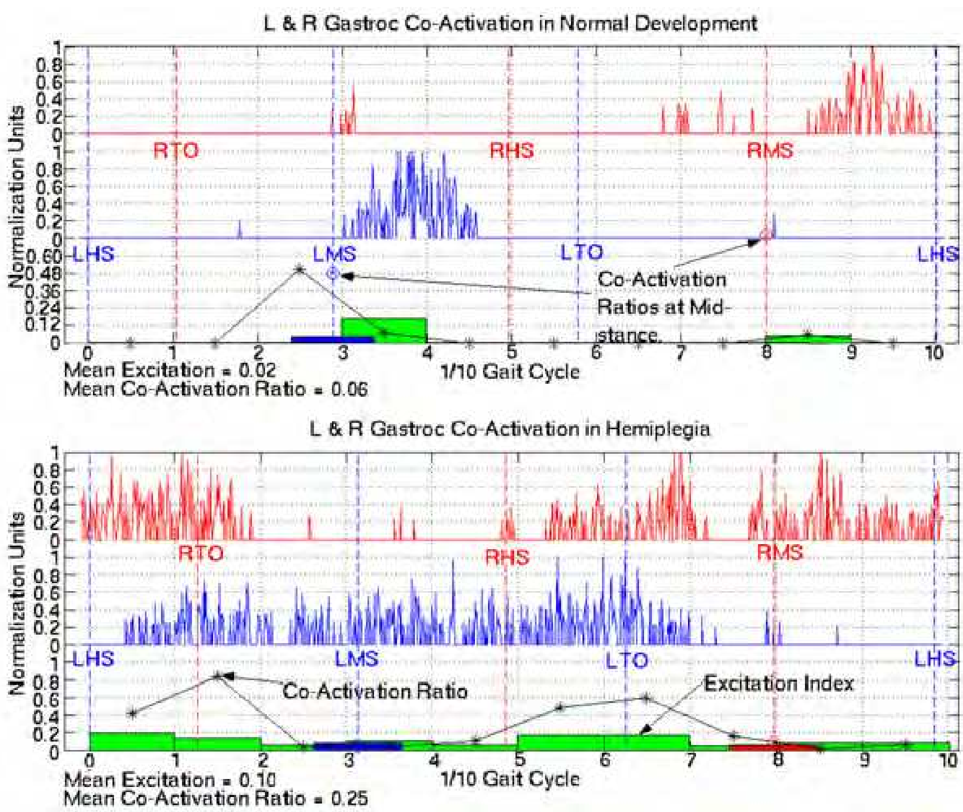


Note: Means are calculated over 14 cycles (140 points).

Fig. 3. Assessment of a Co-Contracting Muscle- This figure illustrates a clear difference between hemiplegia and normally developing gait cycles on a 1/10 cycle by cycle basis.

Turning to the original motivation for this work, Figure 4 demonstrates the use of the assessment method to explore excitation in contralateral muscles. Our hypothesis states that if "mirrored excitation" exists, it is most likely to be seen at mid-stance/mid-swing, where the muscles of the "swinging" limb should be inactive and the supporting limb's muscles should be most active. While it is not the intent of this chapter to prove or disprove our working hypothesis, some results will be presented in order to demonstrate the efficacy and efficiency of the method of assessment outlined and advocated.

With regard to mirrored excitation, it is expected, that the excited muscle will be mirrored onto the inactive muscle. In the example below, for the normally developing subject, it can be seen that the co-activation ratio for this gait cycle is highest at mid-stance of both limbs. This is actually an atypical gait cycle, chosen so the numbers would be large enough to be seen on the graph. The mean values were in fact 0.07 on the left and 0.04 on the right. An examination of the means of these values over the 10 cycles, in the subject with hemiplegia, reveals a mean excitation index on the left of 0.14 (slightly higher than the value of the complete gait cycle) and a mean ratio of 0.44 (almost twice the value for the complete cycle). While the values at mid-stance on the right are 0.08 and 0.62 respectively. From this, one would conclude that there is an influence at left mid-stance, but without the greater excitation index at right mid-stance, information from other muscles would be needed to draw any conclusions.



Note: Mid-stance (L & R MS) values are calculated from data taken between 1/20th cycle on either side of the mid-stance point.

Fig. 4. Left and right side co-activation.

The previous two graphics presented EMG data in raw, rectified, normalized form, with the assessment analysis being performed on this raw data. This is simply the authors' preference and should not be interpreted as the only way the analysis can be done. The next graphic, Figure 5, presents a comparison of the analysis performed on both raw and filtered data. To be noted here is the fact that both profiles, that of the excitation index and the co-activation ratio appear very much alike. The mean excitation index is slightly less (0.06 vs. 0.10) while the mean co-activation ratio is slightly greater (0.37 vs. 0.25). Each of these differences makes sense when considering what filtering does. By lowering the peak values of the EMG data, the excitation index has a smaller numerator and thus a smaller value for each 1/10 cycle. At the same time that peaks are made lower the data is spread over a larger region of time, this causes the regions with the higher peaks to take up greater area. Since the co-activation ratio is calculated by dividing the smaller number by the larger, an increase in the smaller number (in this case) is reflected by a larger ratio.

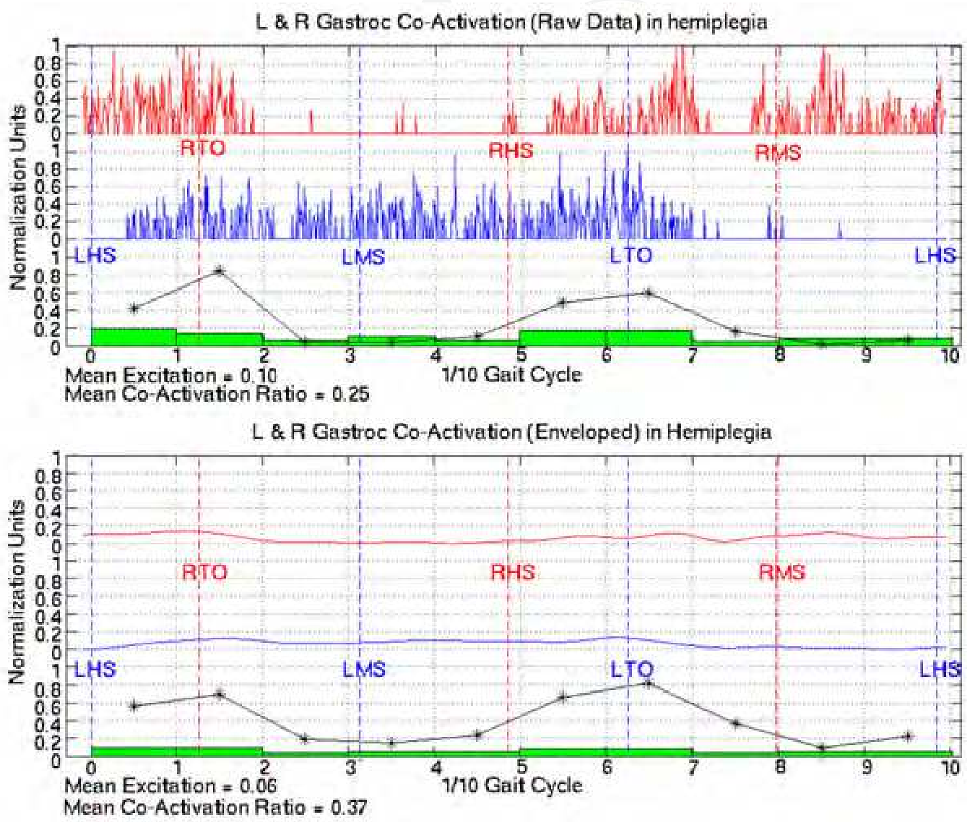
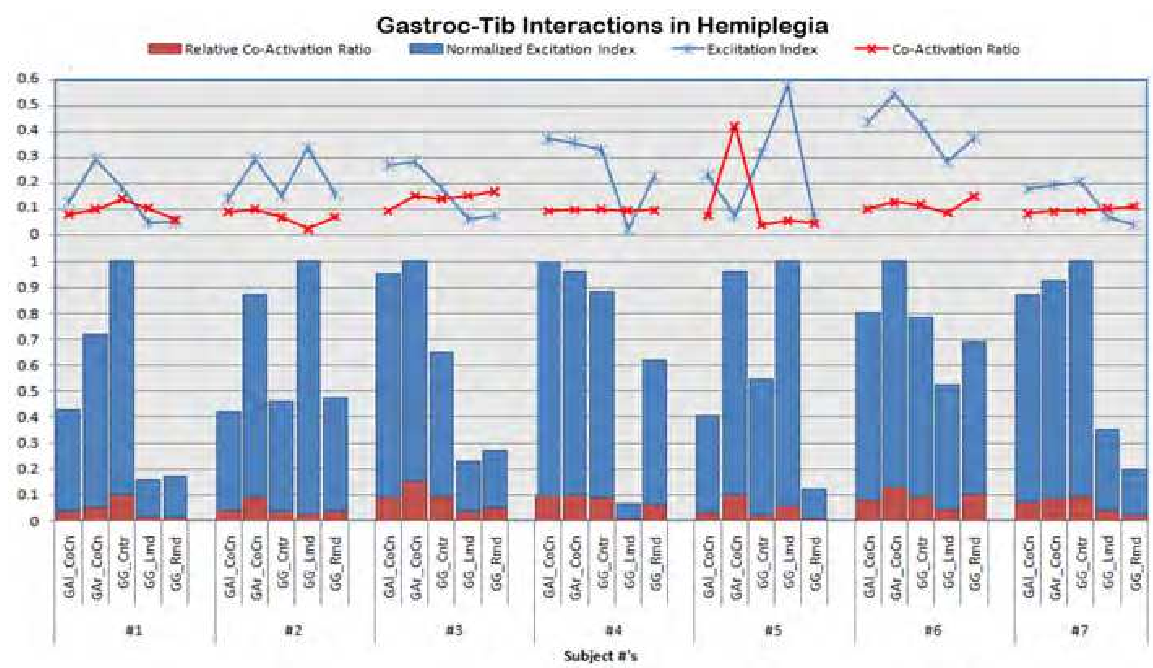


Fig. 5. Raw and filtered EMG and their resulting parameters.

The presentation of this data in a meaningful way so that different muscle groups among different subjects can be compared, is not a trivial matter. A method for plotting twenty points per muscle per gait cycle for several muscles of interest must not overwhelm the reader with data while at the same time allow a readily recognizable comparison of pertinent information. In the case of the authors, the interest is in comparing contralateral co-activation with co-contraction in both limbs. At the least this involves three muscle groups, adding to this is the desire to compare these muscle groups at particular points in each gait cycle (mid-stance) thus adding an additional two comparison groups to the representation task.

The method to be suggested here will utilize two distinct graphing methods; in the first, line graphs will present the excitation index and co-activation ratios in their pure calculated form. In the second, bar charts will compare normalized values of the excitation indices. It is felt that both are of value and both have a valid place. The bar charts provide an immediate means of comparing muscle groups within the same subject. Line graphs provide a means of comparing data across subject.

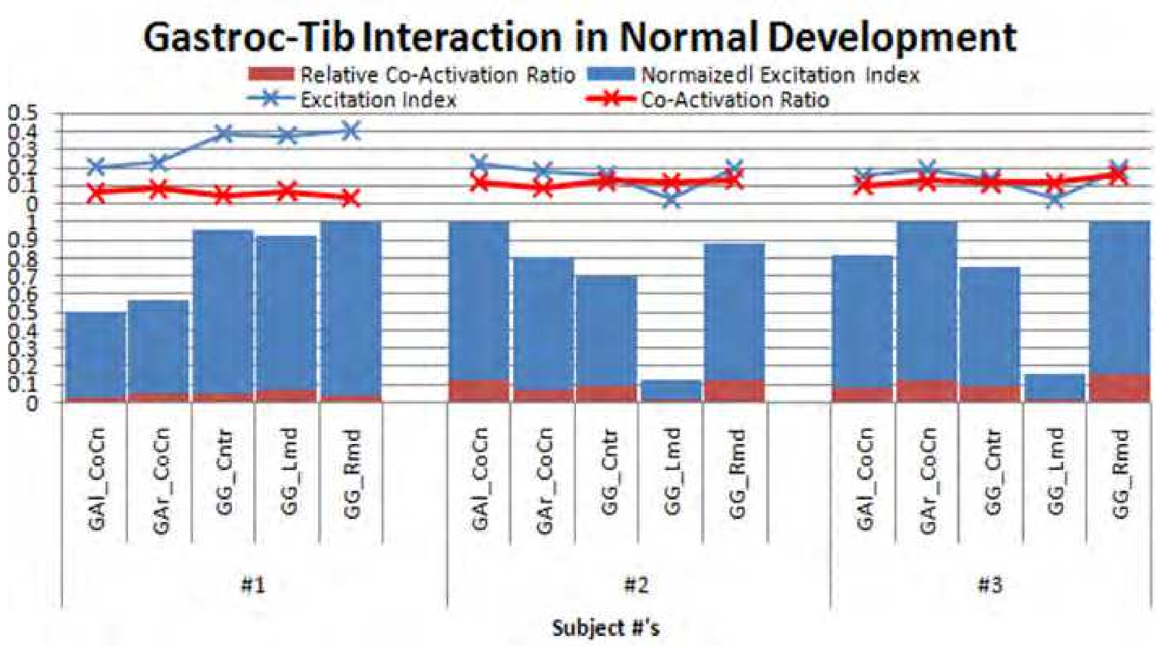
To construct the graphs, the authors calculate a mean value of each parameter over the ensemble of gait cycles recorded for each subject. From each ensemble of muscle groups to be compared, the maximum muscle excitation index is chosen and all other excitation indices are normalized on this value. Each normalized value now represents the comparative excitation of each muscle group. Since the co-activation ratio represents the comparison of activation between the two muscles of a given group, multiplying the normalized excitation index by this ratio, preserves its comparative property between the groups. The process lends itself well to a graphical representation by means of a stacked column graph. Figure 6 presents a comparison of Gastrocnemius-Anterior Tibialis interaction in seven subjects with hemiplegic cerebral palsy. The data presented represent a number of interesting interactions between the groups. In the third, fourth and sixth subject, co-contraction is the dominant muscle activity. In the other 4, the dominant activity is the co-activation between the right and left sides. In two of the subjects (#1 and #7) this dominance is seen across the entire gait cycle, in the remaining two the dominance occurs only at the points of mid-stance. While the method of presenting the normalization of means clearly has its value in the intragroup comparison for a single subject, it can give misleading results when comparisons are made across subjects. To address the issue, data is presented as it was before normalization. These two added sets of data insures that a very strong excitation, when normalized to unity, is not seen as comparable to a weak excitation that might happen to the maximum value for another subject.



Legend: GAl = Gastroc-Tib left, GAr = Gastroc-Tib right, CoCn = Co-contraction,
Cntr = contralateral co-activation (measured over the complete cycle), GG = Gastroc-Gastroc, Rmd = Right Mid-Stance, Lmd = Left Mid-Stance
Bar charts are normalized data, line graphs are actual values.

Fig. 6. Excitation indices and co-activation ratios for seven subjects

In the example presented in Figure 6, maximum excitation is almost the same for subjects 1, 2, 3, 4, and 7. Comparison of these subjects would be fairly reasonable. Comparison of these with subjects 5 and 6 becomes more problematic because their maximum excitations are clearly more intense.
As a final step Figure 7, below, provides a comparison to data from three normally developing subjects for the same muscle groups. This graph demonstrates the value of both



Legend: GAl = Gastroc-Tib left, GAr = Gastroc-Tib right, CoCn = Co-contraction,
Cntr = contralateral co-activation (measured over the complete cycle), GG = Gastroc-Gastroc,
Rmd = Right Mid-Stance, Lmd = Left Mid-Stance
Bar charts are normalized data, line graphs are actual values.

Fig. 7. Normalized mean excitation indices for three normally developing subjects

the bar and line graphics. While the bar graphs suggest that it may not be unusual for co-activation across the body to exist at mid-stance, the line graphs make it clear that it is not a dominant form of excitation. The most obvious difference between the normally developing subjects and those with hemiplegia are the obviously consistent indices and ratios seen in the normal developing subjects. All interaction in this data seem to be at about the same level. The slight elevation in excitation index of contralateral muscle groups of subject #1 may not be indicative of all normal subjects, a larger subject population would be necessary to identify true trends in normal developing subjects.

While the normalization method presented above may provide a good tool for visualization, the set of values calculated from tenths of a gait cycle should easily form the basis of a statistical analysis using a paired t-test or a two-way ANOVA.

4. Conclusion

It has been the purpose of this chapter to present a method whereby the co-activation of two muscles can be compared and presented to the clinician in a meaningful way. It has been shown, with the use of both stylized EMG data, and real data from ongoing experimentation, that the method presented provides two unique numbers which completely define the state of excitation of a muscle group. It has been demonstrated further that this method overcomes the pitfalls of previous attempts. Among its attributes are the method's ability to deal with both active and inactive muscle activity and to easily fit into many standard gait analysis reports.

The method begins with a normalization that combines two previously described methods. This combination of normalization on peak values and mean values of the data set itself eliminates drawbacks of both methods. Additionally it eliminates the need for a maximal contraction which many of those in the cerebral palsy population cannot perform.

The assessment method provides two numbers, the first, the Excitation Index, measures the activation of both muscles of interest in combination. The second number, the Co-activation Ratio, provides a measure of each muscle's excitation relative to the other. In combination, the two measures completely define the comparative excitation of any two muscles of interest.

The chapter presents several graphical methods of presenting the assessment method so that it can be used to compare a single set of muscles in a gait analysis, or to compare multiple groups of muscles across a sample population.

Although the data analyzed have largely been raw, unfiltered EMG data, the method can be applied equally as well to filtered "enveloped" data. In the case of one such analysis presented, while the mean values were somewhat different for filtered data, the overall profiles of both the excitation indices and the co-activation ratios remain consistent over the gait cycle presented.

Finally the chapter has demonstrated that the method can be applied to ongoing research in the author's laboratory. The authors believe that this demonstrates the value of the method in a real application.

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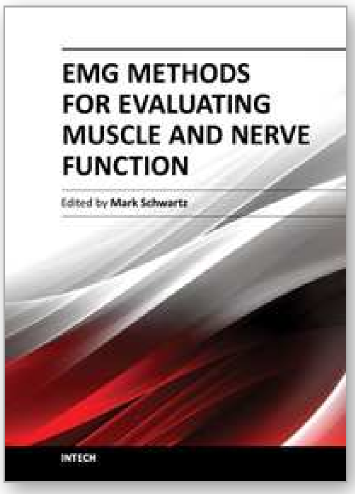

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This first of two volumes on EMG (Electromyography) covers a wide range of subjects, from Principles and Methods, Signal Processing, Diagnostics, Evoked Potentials, to EMG in combination with other technologies and New Frontiers in Research and Technology. The authors vary in their approach to their subjects, from reviews of the field, to experimental studies with exciting new findings. The authors review the literature related to the use of surface electromyography (SEMG) parameters for measuring muscle function and fatigue to the limitations of different analysis and processing techniques. The final section on new frontiers in research and technology describes new applications where electromyography is employed as a means for humans to control electromechanical systems, water surface electromyography, scanning electromyography, EMG measures in orthodontic appliances, and in the ophthalmological field. These original approaches to the use of EMG measurement provide a bridge to the second volume on clinical applications of EMG.

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