

# Computer Algorithms to Characterize Individual Subject EMG Profiles During Gait

Ross A. Bogey, DO, Lee A. Barnes, MA, Jacquelin Perry, MD

**ABSTRACT.** Bogey RA, Barnes LA, Perry J. Computer algorithms to characterize individual subject EMG profiles during gait. *Arch Phys Med Rehabil* 1992;73:835-41.

• Three methods of precisely determining onset and cessation times of gait EMG were investigated. Subjects were 24 normal adults and 32 individuals with gait pathologies. Soleus muscle EMG during free speed level walking was obtained with fine wires, and was normalized by manual muscle test (%MMT). Linear envelopes were generated from the rectified, integrated EMG at each percent gait cycle (%GC) of each stride in individual gait trials. Three methods were used to generate EMG profiles for each tested subject. The ensemble average (FAV) was determined for each subject from the mean relative intensity of the linear envelopes. Low relative intensity or short duration EMG was removed from the ensemble average to create the intensity filtered average (IFA). The packet analysis method (PAC) created an EMG profile from the linear envelopes in successive strides whose respective centroid %GC locations were within  $\pm 15\%$ GC of each other. Control values for onset and cessation times of individual gait trials were calculated after spurious outliers were removed. Mean onset and cessation times across subjects for control values and the experimental methods (EAV, IFA, and PAC) were calculated. Dunnett's test ( $p < .05$ ) was performed to compare control and experimental groups in patient and normal trials. EAV differed from control values for onsets ( $p < .01$ ), cessations ( $p < .01$ ), and durations ( $p < .01$ ) in both normal and patient trials. IFA and PAC had no significant differences from control value means. IFA was selected for clinical use as automatic analysis could be performed on all trials and a minimum number of decision rules were needed.

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**KEY WORDS:** *Electromyography; Gait; Timing*

Human walking relies on the coordinated action of 28 major muscles to control the jointed trunk and limbs, and to generate the forces needed to counter gravity and propel the body forward with minimum energy expenditure.<sup>1</sup> The muscles act in groups and most also have more than one function. When any of the muscles involved in the gait process do not perform normally, the person's walking pattern may be significantly altered.<sup>2-8</sup> Many types of pathology (cerebral palsy, stroke, etc.) may decrease the ability of a muscle to generate the needed force or create excessive action at inappropriate times.<sup>4</sup> Often these abnormalities introduce unusual demands on other musculature.

To diagnose a patient's gait dysfunction, various methods of measurement of muscle function have been devised.<sup>3,4,6,9-28</sup> Muscle action inferred from either observed or instrumented recording of the patient's walking pattern is commonly used, but this does not separate primary pathology from substitutive effort.<sup>7,29-31</sup> Estimates of gait muscle action from manual muscle testing may be misleading because the reflex responses of patients during gait are often different.<sup>7,32</sup> Dynamic electromyography (EMG) offers a means of directly tracking muscle activity. The myoelectric signal sufficiently parallels the intensity of muscle action to serve as a useful indicator of its mechanical effect.<sup>33-39</sup> Delineating the changes in phasing, duration, or magnitude of muscle action associated with a person's pathological gait pattern,<sup>40,41</sup> however, is difficult due to the complexity of the EMG record. Its multispikes, random amplitude quality defies simple interpretation. To overcome this limitation, multiple processing and interpretive techniques have evolved.

Any clinically relevant representation of an individual's EMG profile during gait must consider both the timing and the relative magnitude of the EMG signal. Much of the previous quantitated definition of muscle action has been limited to defining the onset and cessation times from the EMG recording while ignoring the relative magnitude of the signal.<sup>9,13,14,18,20,26,42-44</sup> Failure to consider the relative magnitude of the EMG signal may result in improperly timed

From the Department of Pathokinesiology Service, Rancho Los Amigos Medical Center, Downey, CA.

This work was supported by grant R01 AM 38713 from the National Institutes of Health, Bethesda, MD.

Submitted for publication March 1, 1991. Accepted in revised form September 4, 1991.

An organization with which the author or one or more of the authors is associated has received or will receive financial benefits from a commercial party having a direct or indirect interest in the subject matter of this article. No such benefit has been conferred directly upon the author or authors.

Reprint requests to Ross A. Bogey, DO, Department of Physical Medicine and Rehabilitation, University of California, Davis, 4301 X Street, Room 2030, Sacramento, CA 95817.

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muscle action of inappropriate intensity being incorrectly labeled as normal.<sup>4</sup> The ability to quantitate the relative intensity of the EMG signal between onset and cessation times is imperative for averaging data from multiple strides.

To overcome this shortcoming, others have displayed the relative intensity of effort as a mean linear envelope of amplitudes at each gait cycle interval.<sup>3,6,11,15</sup> This ensemble averaging (EAV) of EMG relative intensity has been the most frequently used method in gait analysis<sup>3,6,11,15,28,35,45,46</sup> and has been previously identified as the best indicator of a subject's "typical" EMG profile.<sup>24</sup> Following rectification and integration of the raw EMG record, the series of mean amplitudes per unit time are calculated for the duration of that muscle's action during the study.<sup>45</sup> These data for multiple strides within a single trial are used to produce an ensemble average for a given muscle. The ensemble average (EAV) method accurately depicts the relative magnitude of EMG activity.

Ensemble averaging of EMG data was not without limitations, however. In the course of analyzing patient data, comparison of the timing of an individual patient record with a single normal record identified notable differences in the patient's function that correlated with clinical expectations. These functional differences were obscured when these same patient records were compared to EMG profiles obtained by ensemble averaging of individual normal records.<sup>11,15,45</sup> The duration of the EMG profile obtained by ensemble averaging appeared to be longer than any normal subject's single stride activity. These differences indicated an inherent flaw in the ensemble averaging technique. The ability to precisely define the onset time, cessation time, and duration of the EMG signal via ensemble averaging has not been documented.

The timing of the electromyogram has important clinical implications. Surgical decisions, such as the choice between tendon transfer and tendon lengthening, may be made solely on whether the muscles are active exclusively in one portion of the gait cycle.<sup>47</sup> As a result of the potential timing inadequacies of ensemble averaging, two additional techniques, the intensity filtered average (IFA) and packet analysis (PAC), were developed to analyze gait EMG.

The IFA method retains the positive attributes of ensemble averaging (ie, relative intensity measurement), while concurrently approximating the mean EMG duration for the individual gait trial. The IFA generates a representative EMG profile by removing low relative intensity or short duration EMG from the ensemble average profile.

The PAC generates a representative EMG profile using the same patient or subject data as the other methods. The onset and cessation values of the PAC are determined by the mean onset and cessation times of the linear envelopes in each stride for each gait trial. The packet analysis EMG profile is obtained by applying standard linear interpolation techniques to the relative intensities of the individual linear envelopes rather than simply determining the mean relative intensity at each percent of the gait cycle.

## METHODS

The purpose of the study was to compare three methods (EAV, IFA, and PAC) of generating a single subject EMG profile from multiple gait strides. Differences in onset and cessation timing for the three methods were compared to statistical controls.

### Subjects

Subjects consisted of 24 normal adults with no known neuromusculoskeletal pathology (22 female, two male;  $26 \pm$  six years) and 32 individuals with gait pathologies (22 women, ten men aged  $31 \pm 23$  years). Gait pathologies were secondary to head trauma ( $n = 4$ ), stroke ( $n = 18$ ), cerebral palsy ( $n = 6$ ), and post polio ( $n = 4$ ). Patients were referred for gait analysis customarily with the objective of defining muscle action as an aid to surgical planning.

Subjects consented to participate following explanation of the procedure and review of the informed consent, as approved by the Institute Review Board, and signed the Rights of Human Subjects form.

### Data Acquisition

Electromyographic (EMG) activity of the soleus muscle was recorded with paired fine-wire electrodes (50 $\mu$  with 2mm bared tips) inserted into the belly of the soleus muscle using Basmajian's single needle technique.<sup>48</sup> Electrode placement was confirmed by electrical stimulation of the muscle through the indwelling electrode, and by voluntary muscle contraction. The EMG system bandwidth was 150-1,000Hz with an overall gain of 1,000.<sup>49,50</sup> The EMG was simultaneously telemetered to a DEC PDP 11/23+ computer by means of an FM/FM telemetry system. A maximum manual muscle test (MMT) was performed to provide a level for normalizing the gait EMG.<sup>51</sup> The MMT value was obtained by having the subjects perform a maximum heel rise test while electromyographic activity, (in mV) was recorded. One hundred percent MMT (100%MMT) was defined as the 20msec interval with the greatest mean intensity during the manual muscle test.

The gait cycle interval and foot support patterns were recorded with footswitches taped to the subject's bare feet. Each footswitch<sup>3</sup> had compression closing contacts located at the heel, first and fifth metatarsal heads, and great toe. Footswitch and EMG data were collected simultaneously while subjects performed a single gait trial that consisted of traversing the middle six meters of a level, ten meter walkway. This test interval was designated by photoelectric cells. After the walking trials, another manual muscle test was recorded to confirm the continued viability of the electrodes.

Footswitch data were used to determine the exact times of the stance and swing periods. The stance percent of gait cycle (%GC) was adjusted to reflect delays in footswitch contact opening and closing.<sup>52</sup> The mean %GC for stance and swing phases were calculated on a VAX 1 1/750 computer.

EMG data were digitized at a rate of 2,500 samples per second using a 12-bit analog-to-digital converter. Digitizing was triggered by lightswitches. All data were printed out in analog form for visual analysis. The digitized EMG data were rectified and integrated. Using a moving window integration scheme a single mean value for a 50 sample interval was calculated, where each sample represented a 0.4msec interval. The beginning of the 50 sample integration period was then incremented by one sample, and the mean value determined for the next 50 samples. The integrated signal was then corrected for baseline noise as determined by a resting run. Stride data were divided into 1%GC intervals with %MMT determined at each percent gait cycle interval.

## Data Processing

Linear envelopes were generated from the rectified, integrated EMG signal for each stride, and were expressed as %MMT for each 1%GC interval.<sup>11</sup> The linear envelope was defined by the region bounded by the onset and cessation of EMG activity and by the curve describing the intensity of EMG activity. From the individual linear envelopes, a representative EMG profile was generated for each subject by each of the three algorithms examined (EAV, IFA, and PAC). Each algorithm used the same EMG data.

For the ensemble average (EAV), the amplitudes of the linear envelopes from multiple strides were summed at each 1% gait cycle interval and an average intensity per interval calculated. Onset and cessations as a percent of gait cycle (%GC) were calculated from the series of strides (fig 1).

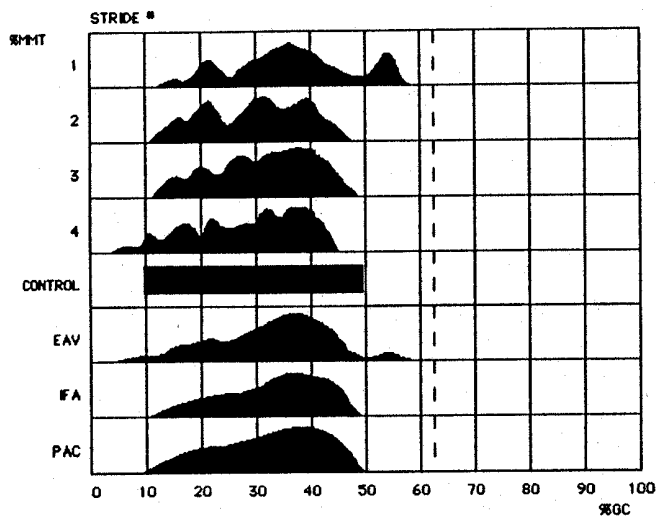


Fig 1-Comparison of the soleus EMG profiles for the EAV, IFA, and PAC methods. Linear envelopes are shown for one patient performing four consecutive free walking strides.<sup>1-4</sup> Time of control value EMG activity (CONTROL) is depicted by a horizontal bar. The EMG profiles for this gait trial as determined by the three experimental averaging techniques (EAV, IFA, PAC) are presented. Percent gait cycle (%GC) is represented on the abscissa; individual ordinate scales are divided into 100 1%MMT increments. End of stance phase is marked by the dashed line at 62%GC.

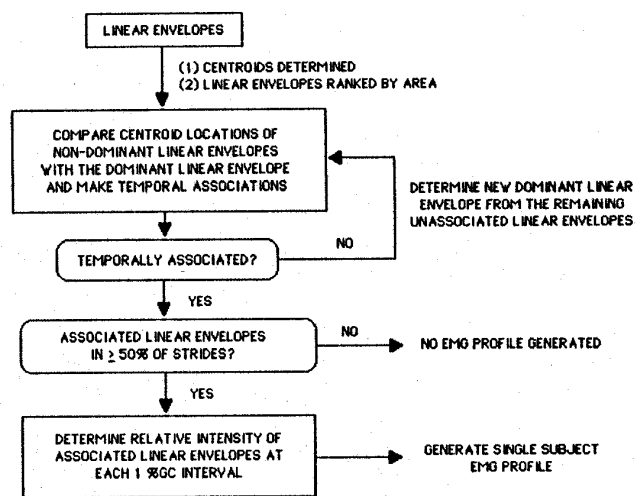


Fig 2-Flowchart of EMG profile determination by the PAC method. The same linear envelopes used in the EAV and IFA analyses were ranked ordered by total area (as determined by integration of the linear envelope curve), and %GC location of the individual centroids determined. The linear envelope with the greatest area was designated the "dominant packet." All other linear envelope centroid locations (in %GC) were compared with the dominant packet. Further analysis was performed on those packets that were temporally related. Temporally related EMG packets were those whose centroid %GC location was  $\pm 15\%$ GC of the dominant packet centroid. Packets not associated with the dominant packet went through this same iterative process again, with the largest remaining packet identified as the new "dominant packet." This process continued until all temporally associated EMG envelopes, present in  $\geq 50\%$  of strides were combined. EMG relative intensity at each 1%GC of the associated packets was calculated by linear interpolation of the linear envelopes.

The IFA differed from the EAV by applying decision criteria to remove low intensity or short duration EMG from the ensemble average. EMG amplitudes less than 5% of the maximum muscle test were excluded from the ensemble average profile (fig 1). In a succession of ensemble average EMG packets, those packets separated by cessation-onset intervals less than 5%GC duration were combined into a single parcel. Similarly, EMG packets (onset to cessation) lasting less than 5%GC were excluded.

The PAC method was an attempt to generate a single subject profile by combining mean onset and cessation timing with a linear interpolation of the relative intensity of the individual stride EMG. In packet analysis initially the onset and cessation times for each linear envelope, and the total area under each individual linear envelope curve were determined. In addition to defining the onset and cessation %GC, the %GC occurrence of the centroid for each linear envelope was calculated for the PAC method only. The centroids (as %GC) were defined by

$$P = \frac{\sum P_k m_k}{\sum m_k}$$

where P represented the location of the linear envelope centroid,  $P_k$  the location of the individual %GC components, and  $m_k$  the %MMT found at those respective %GC locations.

The linear envelopes in each gait trial were sorted in decreasing order of EMG total area. The linear envelope with the largest area as determined by integration was designated as the dominant packet (fig 2). PAC associated temporally related linear envelopes in successive strides by comparing the centroid locations of the remaining (nondominant) packets with the timing of the dominant packet in terms of percent gait cycle occurrence. Linear envelopes whose centroid occurrence were within  $\pm 15\%$ GC of the dominant packet centroid were considered to be temporally related to that linear envelope. Mean onset and cessation times were calculated for each group of temporally related packets for each subject, and EMG relative intensity at each

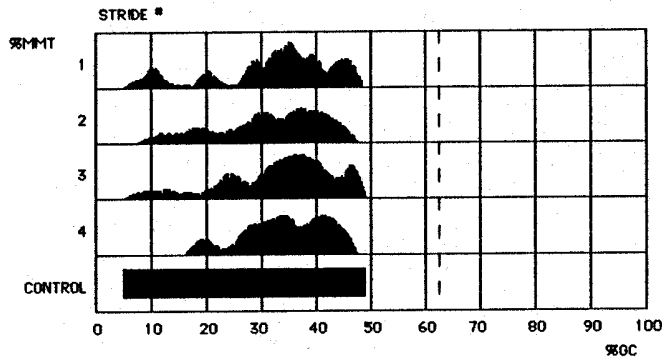


Fig 3-Determination of reference ("control") value onset and cessation times. Linear envelopes are shown for one normal subject performing four consecutive strides of free speed walking. All strides had consistent cessation times. The first three strides had consistent onset values. The fourth stride had a delayed onset with respect to group mean values ( $>2$  standard deviations). The calculated onset time for the control value was based on the onset times of the first three strides only. Control value cessation time was calculated from the cessation %GC of all four strides. Control value EMG duration is depicted by the solid line (CONTROL). Percent gait cycle is represented on the abscissa; percent manual muscle test is represented on the ordinate for each stride.

%GC of the related packets was determined by linear interpolation of the individual linear envelopes. All packets not temporally associated with the dominant packet were ranked by area and the same temporal relationship analysis

repeated for the remaining linear envelopes. This continued until all possible associated packets (present in  $\geq 50\%$  of strides) were grouped, and a representative EMG profile was generated by the PAC method for each subject or patient (fig 1).

### Statistical Analysis

As a basis for assessing the validity of the three methods, a control value for each individual gait trial was determined. In each subject or patient trial, the mean onset and cessation values from the series of strides were calculated after values greater than two standard deviations from the series mean were removed (fig 3). This procedure yielded the control values for onset and cessation times for that trial. Experimental (EAV, IFA, PAC) and control value across-subject mean onset and cessation times for normal and patient populations were computed from the individual onset and cessation values. Comparisons between the three analysis methods and the control values were made for onset time, cessation times, and EMG duration. Total EMG for any single subject did not differ by more than 5% (3.1%) regardless of "averaging" method. As a result no further comparison was made to examine the differences in relative intensities profiles between experimental groups. Data for the normal subjects' and patients' free speed walking were tested separately.

Statistical analyses were performed using StatView 512+ statistical software. Differences between the experimental methods were determined by repeated measures ANOVA. A post-hoc Dunnett's test<sup>53</sup> was performed to find significant differences between a control mean and the three experimental groups. Significance level for Dunnett's test was set at .05.

## RESULTS

### Normal Subjects

The ensemble average EMG duration was significantly greater ( $p < .01$ ) than the control group duration in normal subjects (fig 4). This increase in EMG duration was the result

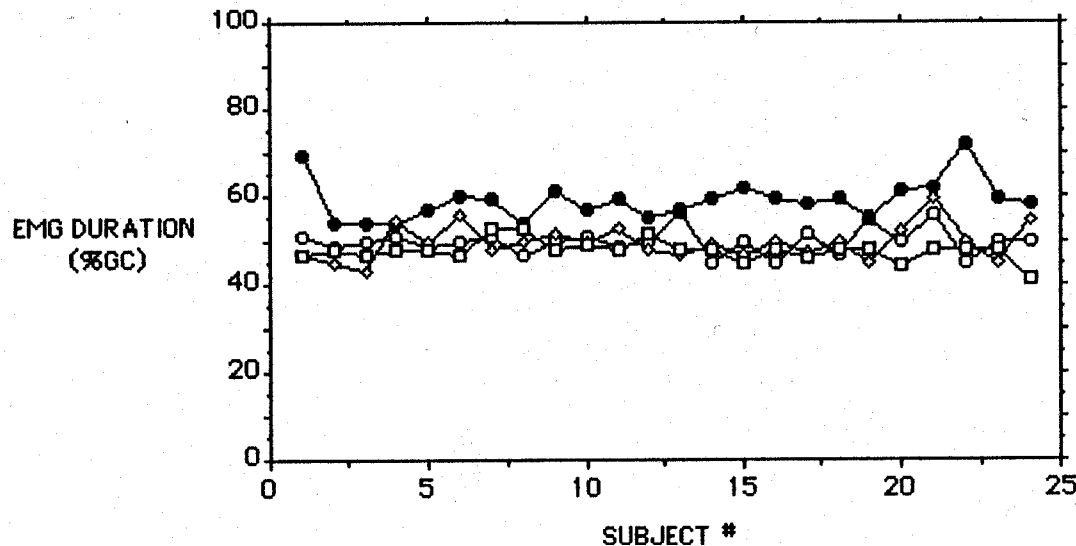


Fig 4--Soleus muscle EMG duration in 24 normal adults. Duration of soleus EMG activity for control values. EAV, IFA, and PAC methods for each subject is shown. Subject number is shown on the abscissa; percent gait cycle duration of soleus activity from multiple strides is shown on the ordinate.  $\bullet$ , control;  $\star$ , EAV;  $\square$ , IFA;  $\diamond$ , PAC.

**Table 1: Comparison of EMG Averaging Methods of Gait Analysis for 24 Normal Adults**

	Onset		Cessation		Duration	
	%GC (SD)	<i>t</i> value	%GC (SD)	<i>t</i> value	%GC (SD)	<i>t</i> value
Controls	9.28 (4.19)	—	59.05 (4.20)	—	49.77 (3.05)	—
EAV	5.82 (4.12)	4.77†	65.15 (4.44)	8.03†	59.33 (4.11)	9.11†
IFA	10.53 (4.68)	1.74	60.10 (4.58)	1.45	49.57 (3.99)	0.18
PAC	11.18 (6.28)	2.31	58.85 (5.25)	0.24	47.67 (2.53)	1.98

Mean and standard deviation values for controls, EAV, IFA, and PAC methods are shown. Dunnett's test *t* scores (\**p* < .05, †*p* < .01) for comparison of EAV, IFA, and PAC with control group values are given.

of significantly earlier onsets ( $p < .01$ ) and later cessation times ( $p < .01$ ) by ensemble averaging (table 1). No statistically significant differences were observed for the IFA or PAC methods for any variable tested in the normal population (table 1).

### Patient Gait

For the patient data, the EAV results were significantly different from control values for onsets ( $p < .01$ ), cessations ( $p < .01$ ), and durations ( $p < .01$ ) of EMG activity (table 2). In all trials, the duration of EMG activity determined by ensemble averaging was greater than control values (fig 5). The onset time as calculated by ensemble averaging were consistently earlier than control value onset times and the EAV cessation times were later in all trials. In contrast to the ensemble averaging technique, neither the IFA nor PAC methods were significantly different in patient trials from the control values for any variable tested (table 2).

## DISCUSSION

The purpose of an EMG recording is to identify the timing and/or relative intensity of muscle function during some activity, either to have a better understanding of normal or to diagnose a cause of pathologic function. The timing of the electromyogram is a necessary but not sufficient determinant of normal muscle function. Examination of the initial

(loading and midstance) soleus activity emphasizes the importance of the EMG relative intensity. Excessive amplitude of correctly timed EMG in these gait phases leads to one of two clinical consequences. In order to achieve near normal motion at the ankle joint antagonistic activity by ankle dorsiflexors is required. This prolonged co-contraction is not a normal nor desired event. With excessive plantar flexor activity, and in the absence of antagonistic muscle response, the appropriate ankle rocker is inhibited and normal gait is not achieved. With this in mind, the current practice of defining as normal EMG activity based solely on correct timing<sup>9,12-14,18,26,42,44</sup> should be examined more closely. It seems logical that any clinically relevant analysis of EMG must examine both the timing and relative magnitude of the EMG signal. Each of the tested algorithms (EAV, IFA, PAC) combined timing and relative intensity of the EMG signal to create a single subject profile.

Following the common assumption that people have some inconsistency from stride to stride,<sup>54</sup> an average of several strides customarily is calculated to obtain an accurate representation of the person's performance. To average the EMG records, the digital values per gait cycle interval for each record are summed. Differences in EMG timing between different strides are not customarily considered.<sup>3,6,11,15,28,35,36,46</sup> Failure to do so results in small (3% to 6%GC) but significantly different timing of the beginning and end of the normal EMG profile. The repeatability of normal function

**Table 2: Comparison of EMG Averaging Methods of Gait Analysis for 32 Individuals With Gait Pathology**

	Onset		Cessation		Duration	
	%GC (SD)	<i>t</i> value	%GC (SD)	<i>t</i> value	%GC (SD)	<i>t</i> value
Controls	92.76 (12.12)	—	60.26 (11.82)	—	67.50 (7.96)	—
EAV	84.93 (12.10)	10.35†	74.07 (11.62)	12.41†	89.14 (4.69)	15.46†
IFA	91.56 (11.37)	1.59	59.55 (11.39)	0.63	67.99 (8.78)	1.17
PAC	94.70 (9.69)	2.42	61.38 (9.79)	1.92	66.68 (7.91)	2.17

Mean and standard deviation values for controls, EAV, IFA, and PAC methods are shown. Dunnett's test *t* scores (\**p* < .05, †*p* < .01) for comparison of EAV, IFA, and PAC with control group values are given.

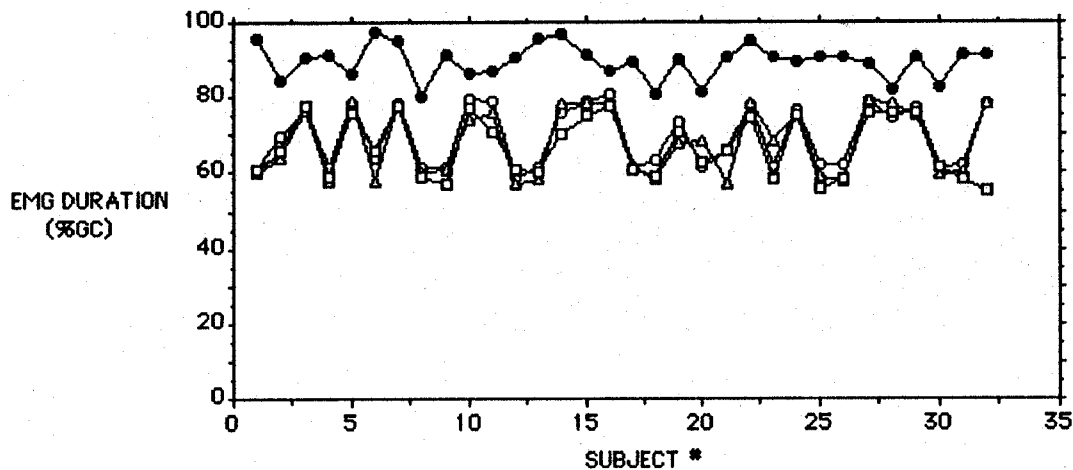


Fig. 5 - Soleus muscle EMG duration in 32 individuals with gait pathology. Duration of soleus EMG activity for control values, EAV, IFA, and PAC methods for each subject is shown. Subject number is shown on the abscissa; percent gait cycle duration of soleus activity from multiple strides is shown on the ordinate. †, control; ★, EAV; ●, IFA; □, PAC.

resulted in such consistent onset and cessation times that these differences have gone unnoticed. In contrast, empirical observation of patient records indicated that they displayed considerable variation in the timing of the electromyograms during sequential strides even though the intensity profiles of the muscle action were similar. The extended duration of the ensemble average profile for patient trials is an indicator of the variability in onset and cessation times in successive strides. The cause of this variability was not evident, but it might be small inconsistencies in the patient's stride mechanics of the individual gait cycles. In each case the variability in timing from stride to stride resulted in an increased duration of the "average" electromyogram (fig 5).

The clinical significance of the artificially extended EMG record is the functional error it implied and possibility of stimulating inappropriate clinical management. For example, the ensemble average record incorrectly identified the onset of normal soleus muscle activity as occurring in the initial half of the loading response. This same trend could occur in a single patient trial as a result of the temporal expansion of the EMG envelope by ensemble averaging. If the patient displayed accelerated ankle plantar flexion, the EMG evidences of premature soleus action could sway the physician to prescribe a rigid orthosis for soleus control when a lighter device might be adequate to support a flaccid footdrop. A recommendation for surgical tendon lengthening to weaken the muscle tension is another potential interpretation of the extended EMG data. The potential for clinical mismanagement, when that management is based on patient EMG timing, is reduced by using the IFA and PAC techniques.

The ensemble average method was clearly shown to have limited clinical utility in gait analysis due to the temporal expansion of the EMG profile that was observed. This tendency toward temporal expansion of the EMG profile by ensemble averaging is increased as the number of strides analyzed increases. Neither the PAC nor IFA method should be effected by the number of strides analyzed in an individual patient trial.

Including low relative intensity EMG in the average profile obscures the determination of essential muscle activity during gait. EMG below the 5%MMT threshold (clinical grade = 2-)

has no functional significance.<sup>55</sup> The elimination of low relative intensity EMG from the ensemble average resulted in an intra-subject profile that approximated the mean timing of the EMG signal. It was felt that short duration (25-40msec) EMG observed in only a few strides has no functional significance in controlling joint motions, and was eliminated from the ensemble average profile as well. The intensity filtered average that resulted from this removal of low intensity and/or short duration activity from the ensemble average was felt to represent the clinically relevant EMG profile for a single subject.

The accuracy of the PAC method equaled that of the IFA in depicting the timing and magnitude of the EMG signals for the normal and patient trials. Greater user intervention was required, however, and the decision rules for the PAC algorithm were more complex. Additionally, a small number of patient trials yielded an EMG profile with PAC analysis that did not meet clinical expectations due to complexity of the patient record, a situation that did not arise with IFA. Thus, the PAC approach offered no advantages over IFA in the clinical setting.

## CONCLUSION

From a comparison of the three averaging techniques it was determined that the IFA technique had the greatest utility in patient and normal trials. Graphics capabilities, in conjunction with the appropriate analysis algorithm, were developed to aid in clinical decision making.

**Acknowledgement:** The authors thank Ernie L. Bontrager, MS, and Joanne K. Gronley, MA, for their assistance on this project.

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- a. B & L Engineering, 3002 Dow Ave., Suite 416, Tustin, CA 92780.