CHAPTER 7

Applications of Electromyography in Ergonomics

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INTRODUCTION

This chapter reviews experimental design considerations and statistical analyses that make it possible to interpret electromyographic (EMG) results accurately. The major portion of the chapter describes how EMG can be used in various applications. Emphasis is placed on the presentation of exemplary literature, describing how EMG has been used to evaluate muscle function. At the end of each section, key points are summarized.

EXPERIMENTAL DESIGN CONSIDERATIONS

Interpretation of the results of an EMG investigation is dependent on the experimental conditions under which the experiment was conducted and the analyses that have been performed. Most errors in interpretation occur because the investigator is trying to over-interpret or read too much from the data when the experimental conditions and EMG assumptions do not warrant such conclusions.

Errors in interpretation usually are due to two problems in experimental control and data treatment. First, the EMG dependent measures are misinterpreted because the experiment was not designed to preserve the EMG-muscle characteristic relationships described in Chapters 5 and 6. For example, if a lifting experiment is performed under free dynamic conditions, factors such as the length-tension and velocity-tension relationships will interfere with the EMG-tension relationship. In such a case, no statements can be made regarding muscle force, and the valid information derived from the study is reduced to a description of the on-off states of the muscle or a characterization of the muscle activity as measured by EMG.

Secondly, the study may not include a complete experimental design that will allow for statistical evaluation of the data. Many factors may influence muscle activity, and the point of an EMG ergonomic study is to evaluate how work place factors such as methods, tool design, and work place layout influence a muscle or a set of muscles. Unless all relevant factors are considered in the experimental design, however, the results of the study may be misleading. If the activity of the forearm muscles is of interest during the use of various tool designs, for example, the effects of tool design and other factors such as method of use or tool orientation also must be included in the experimental design. If only the tool design is considered, any interactions affecting muscle activity may go unnoticed. There may be no main effect resulting from tool design, but there may be a very significant interaction between tool design and method of use. Such a trend would not be identified without a proper experimental design and evaluation.

As described in earlier chapters, normalization procedures should be used if comparisons are to be made between muscles and subjects. This normalization is necessary because the differences between these factors may be masked. Furthermore, advanced statistical analysis techniques make assumptions regarding the distributions of the dependent measures. These assumptions may not hold if the EMG signal is expressed in terms of microvolts. If they are processed in terms of normalization techniques, however, further analyses are justifiable.

INTERPRETATION THROUGH STATISTICS

A sufficient number of subjects is important when statistical comparisons are intended, to state accurately that one particular work place or method causes a change in muscular activity, muscle force, or fatigue compared with other work positions. Statistical comparisons are needed to determine whether the trends observed in the data are real trends or are due to chance and also to determine the relative contribution of the various effects of the main factors and their interactions.

Comparisons can be made between EMG data sets to determine the significance of one or more work place factors. The techniques that usually are used to make comparisons between one work place factor are the t-test or the one-way analysis of variance (ANOVA). The t-test technique statistically evaluates whether the mean behavior of two groups of EMG data is significantly different. The ANOVA compares the variances between the two or more groups of data. These trends can be evaluated by applying *post hoc* analysis techniques.

Often the effects of several work place factors are of interest. In this case, the effect of each factor and their interactions are of interest. These statistical comparisons usually are best performed by evaluating the variance between the cells of the experiment. These cells represent the combined data that are due to the combination of main work place effects. A two-way or multifactor ANOVA can be used to evaluate the significance of these effects. As with the one-way ANOVA, several *post hoc* follow-up tests are available to interpret the trends. Multiple regression analysis techniques also are used sometimes to build a model of the factors that contribute to the EMG response. In this manner, the amount of variance accounted for by the work place factors can be evaluated in the form of an R squared statistic.

In many EMG studies, the influence of work place factors on the collective behavior of several muscles is of interest. Once the data is normalized, these statistical comparisons usually are performed in multivariate and univariate terms. Multivariate statistics such as multivariate analysis of variance (MANOVA) are used to determine whether several muscles, as a group, respond in a significantly different manner to experimental conditions. Univariate analysis of variance (ANOVA) and discriminate analysis techniques are used as a follow-up to significant MANOVA analyses to determine which individual muscles contribute the most to the multivariate significance. Finally, follow-up post hoc tests, such as Duncan range tests, Tukey tests, and cluster analyses, are used to determine which individual conditions are quantitatively statistically different from one another.

Because statistical analyses options are extensive and can comprise a book in themselves, it is recommended that the reader consult a statistical expert or investigate statistical analysis references when planning and analyzing EMG studies of ergonomics.

ELECTROMYOGRAPHIC RELATIONSHIPS AND THEIR APPLICATIONS

As mentioned throughout most of the previous chapters, the relationship between the EMG signal and the variable of interest is dependent on many factors. These factors include experimental design, normalization techniques, signal processing, and analysis structure. This section discusses these factors collectively as a function of the EMG relative to the ergonomic intent of the studies. Throughout this section, example studies will be discussed that use these EMG relationships and various recording and preparation techniques to derive knowledge about ergonomics. Some of the studies discussed below will point out differences in many aspects of the EMG studies such as recording techniques, processing, and statistical analyses. Then, as more studies are discussed, only the unique features of the studies will be mentioned.

On-Off State of Muscle

Historically, the evaluation of the on-off state of the muscle has regularly been evaluated by EMG. As discussed in Chapter 5, the experimenter simply would observe the raw EMG signal and note when the muscle was active. Most studies that now investigate the on-off state of the muscle are interested in the phasing of the EMG activities under various experimental conditions. Maton et al, using raw EMG, investigated the activity of the elbow extensor muscles during fast and slow braking movements of the arm.[1] An example of these results are shown in Figure 5-8 of Chapter 5. This study was qualitative in that no statistical analyses of the on-off muscle states were performed. This figure, however, demonstrates that more synergistic activity of the muscles occurs under fast motion conditions.

A quantitative evaluation of muscle on-off state was performed by Marras and Reilly, using statistical analyses of muscle event times derived from processed EMG.[2] They were interested in how the patterns of trunk muscle activation changed as the angular velocity of the trunk increased during controlled simulated lifting motions. They statistically compared the event times at which 10 trunk muscles began to activate, reached their peak activities, and terminated their activities as a function of various velocities of motion. A summary of the t-test comparisons of these event times is shown in Figure 7-1. The statistically significant differences were used to construct networks that described the relative phasing and cooperation of these 10 muscles as a function of the trunk velocity. An example of such a network is shown in Figure 7-2. These networks were later used along with EMG force information as inputs to a biomechanical model[3] that was capable of predicting the relative compressive and shear loads on the spine that were due to trunk motion.

These examples show that the muscle on-off information derived from EMG signals is used for two main purposes in ergonomic studies. First, they are used to describe which muscles are active as a function of the work place conditions. Second, muscle phasing and coactivation information can be used in conjunction with other types of EMG force information to assess the loading of joints.

Muscle Force

As mentioned in previous chapters there are several ways to interpret muscle force via EMG. Indicators of muscle force range from estimates of percent of muscle usage to quantitative estimates of the newtons of force present within a muscle during an activity. The degree of quantification possible depends upon the experimental conditions and the experimental control present during the experiment. Examples of the various interpretations of muscle force will be presented here.

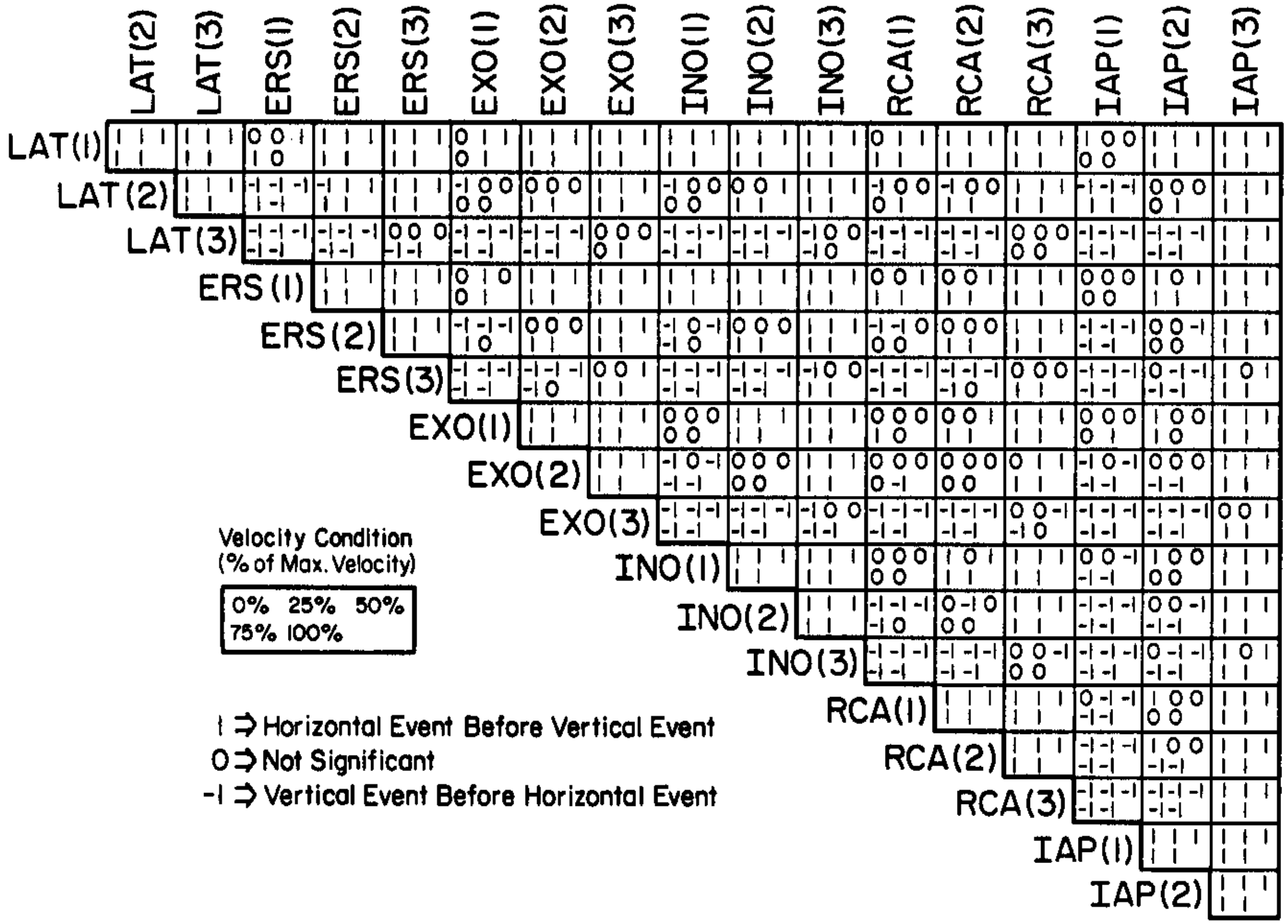

FIGURE 7-1

Summary of significant differences between event times under different conditions. This summary represents a statistical analysis of muscle event times (t_1 = on time, t_2 = peak, t_3 = end time) that are directional. The figure margins represent the muscles considered along with the event time (1, 2, or 3). The experimental conditions are represented by a cell position shown in the legend. If a "1" appears in a cell, the row event preceded the column event and the difference was statistically significant. If a "0" appears in a cell, there was no statistically significant difference in occurence time between the row and column event. If a "-1" appears in a cell, the column event preceded the row event and the difference was statistically significant.

Reprinted with permission from Marras WS, Reilly CH: Networks of internal trunk loading activities under controlled trunk motion conditions. Spine 13:661-667, 1988, Figure 5.

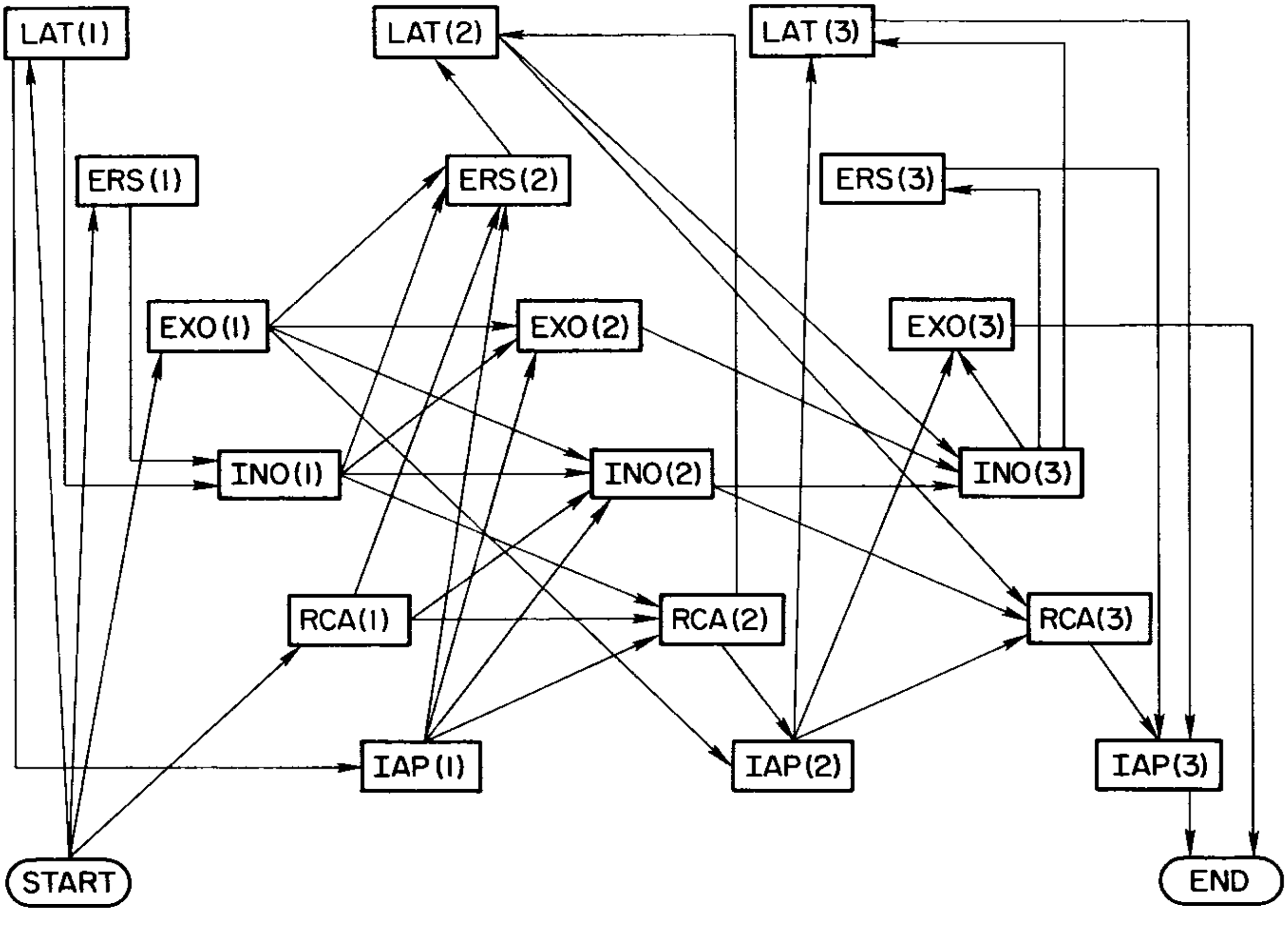

FIGURE 7-2
Network of event-occurrence sequences for isometric exertion.

Reprinted with permission from Marras WS, Reilly CH: Networks of internal trunk loading activities under controlled trunk motion conditions. Spine 13:661-667, 1988, Figure 6.

Muscle Usage Through Normalized Activity Level

One of the most widely used techniques uses EMG to measure the degree of muscle activity required to perform in ergonomic applications. This direct measure is straightforward and simple to use and assists the ergonomist in determining how active a particular muscle is throughout an exertion. It should be emphasized that this measure is not an indicator of muscle tension, but merely a measure of the degree of muscular activation solicited from the muscle. The advantage of this measure is that the data can often be collected on the factory floor without affecting job performance.

To use this measure, one must first determine the EMG signal produced by a maximum contraction. Typically, this effort is elicited from the muscle while the muscle is in the same position required by the work or task under investigation. The EMG activity level (most likely a processed form) during this maximal contraction is recorded and used as the common denominator for estimates of the level of EMG activity required for performance of other tasks. Either the maximum or mean activity level may be used for this purpose. In this manner, the percentage of muscle activity relative to the maximum voluntary muscle contraction (MVC) for a given muscle is obtainable. (Also see Chapter 5.)

Many examples of the use of normalized activity level exist in the literature. These studies typically

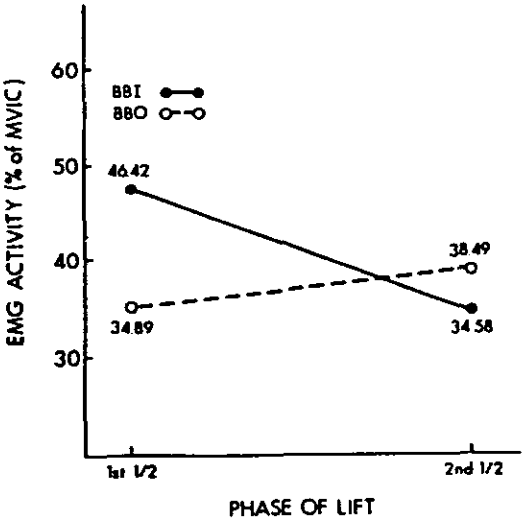

FIGURE 7-3

Interaction between style of lift and phase of lift for erector spinae muscle EMG activity (AB interaction).

Reprinted with permission from Delitto RS, Rose SJ, Apts DW: Electromyographic analysis of two techniques for squat lifting. Phys Ther 67:1329-1334, 1987, Figure 3.

investigate changes in work method, work place layout, tool design, or the reaction of the musculoskeletal system resulting from work conditions. First, examples of method comparisons will be discussed. Delitto et al observed the activity levels of the erector spinae muscles and the oblique abdominal muscles as subjects performed two methods of squat lifting.[4] In this study, subjects were asked to exert isometric MVCs contractions with the erector spinae muscles as they executed a prone position upper-torso lift while resistance was applied bilaterally to the shoulders. The MVCs of the oblique abdominal muscles were solicited with the subject attempting to perform a partial sit-up while resistance was applied to the shoulders bilaterally. It was assumed that these muscle positions were comparable to those used during two types of squat lifts. The EMG signals were processed with a linear envelope detector. The EMG signals and two switch signals that indicated when the lift began and ended were recorded with a strip chart recorder. Using these maximums to normalize the EMG data, these researchers were able to represent each exertion as a percentage of the maximum muscle activity and test the data statistically across activities. Table 7-1 shows the means normalized EMG activities represented as a function of the experimental conditions and Table 7-2 shows a three-way ANOVA used to statistically evaluate these results. Table 7-2 indicates that three significant interactions involving lift method, timing (phase), and load magnitude were found to have an effect on the amount of EMG activity. This table indicates that no significant phase effect (B) is present. As shown in Figure 7-3, however, there is a significant interactive effect between style of lift (A) and phase (B). Such interactions would not be identifiable without a proper experimental design and a formal statistical analysis. In this manner, the study was able to identify the lifting method that offered the most protection to the trunk muscles under various circumstances.

Bobet and Norman also investigated methods of carrying loads, load magnitude, and the duration of load carrying on the activity of the shoulder, back, and leg muscles.[5] This study also normalized the EMG contraction levels; however, the normalization was performed relative to the mean of two 1-second 50% of isometric MVCs. Because the task involved walking and carrying, the EMG signals were transmitted via telemetry to a FM recorder. The average full-wave rectified EMG was used as the dependent measure in this study. After statistical transformation of the data set, the results were tested with a three-way ANOVA procedure for statistical significance. Significant effects were further analyzed by post-hoc analyses. The analysis of the data indicated that only the three way interaction of effects were statistically significant. This study emphasizes the importance of proper statistical analyses. Here, only unique combinations of method of carrying, load magnitude, and duration affected the activity of the muscles. These trends would be very difficult to detect without such statistical analyses.

Secondly, EMG activity level is often used to evaluate work positions or work place layout. One of the most common aspects of the work place investigated is that of sitting position during work. Schuldt et al investigated the effects of sitting posture, hand-arm movement, and arm rests on the activity of neck and shoulder muscles.[6,9] In these studies, electronics assembly workers were studied while performing a simulated work task. Even though the task involved movement of the arms, the positions of the neck and shoulder muscles were considered static during the work. Thus, this study would not violate EMG sampling assumptions. Isometric MVCs of each muscle, recorded while in the sitting position, were used to normalize the activity levels in this experiment. Figure 7-4 shows the isometric positions used for EMG normalization for the muscles of interest. The location of the electrodes used to record muscle activities is shown in Figure 7-5. The EMG dependent variables consisted of full-wave rectified and time averaged EMG

TABLE 7-1

Mean Percentage of Maximal Voluntary Isometric Contraction of Erector Spinae and Oblique Abdominal Muscle Electromyographic Activity During Lifting[a]

	Erector Spinae		Oblique Abdominal	
Style/Phase/Load[b]	$\bar{X}$	s	$\bar{X}$	s
BBI lift (A1)				
First half (B1)				
Light (C1)	27.84	15.91	10.76	8.86
Moderate (C2)	48.91	18.21	29.02	27.12
Heavy (C3)	64.10	18.76	44.85	38.72
Second half (B2)				
Light (C1)	19.29	8.94	6.51	5.16
Moderate (C2)	35.91	12.01	12.80	11.09
Heavy (C3)	48.53	14.35	26.49	21.59
BBO lift (A2)				
First half (B1)				
Light (C1)	24.08	12.36	13.68	16.75
Moderate (C2)	35.03	14.19	26.49	21.59
Heavy (C3)	45.58	17.45	44.21	35.84
Second half (B2)				
Light (C1)	24.40	12.78	6.97	7.72
Moderate (C2)	39.77	14.93	11.13	10.06
Heavy (C3)	51.28	15.67	18.47	14.79

[a] Reprinted with permission from Delitto RS, Rose SJ, Apts DW: Electromyographic analysis of two techniques for squat lifting. Phys Ther 67:1329-1334, 1987, Table 1.

[b] BBI = back-bowed-in; BBO = back-bowed-out

TABLE 7-2

Three-Way Analysis of Variance for Repeated Measures for Erector Spinae Muscle Electromyographic Activity During Lifting[a,b]

Source	df	SS	MS	F
BBI lift vs BBO lift (A)	1	966.09	966.09	20.20[c]
Error	18	1704.94	94.72	
First half vs second half (B)	1	1076.97	1076.97	4.90
Error	18	3952.62	219.59	
Load (C)	2	31185.90	15592.95	167.30[c]
Error	36	3319.20	92.20	
AB interaction	1	3672.50	3672.50	15.69[c]
Error	18	4212.90	234.05	
AC interaction	2	708.22	354.11	11.63[c]
Error	36	1095.84	30.44	
BC interaction	2	10.58	5.29	0.08
Error	36	2260.44	62.79	
ABC interaction	2	379.96	189.98	8.28[c]
Error	36	826.20	22.95	

[a] Reprinted with permission from Delitto RS, Rose SJ, Apts DW: Electromyographic analysis of two techniques for squat lifting. Phys Ther 67:1329-1334, 1987, Table 2.

[b] BBI = back-bowed-in; BBO = back-bowed-out

[c] $p < .01$

signals using a 1.1-second time constant. The data were recorded on heat sensitive paper. Figure 7-6 shows an example of the varied range of EMG responses that were collected from the 10 subjects in this study. This study used a series of Student's t-tests to determine the statistical significance of the results. In this manner, the effects of sitting postures and their interaction with arm supports and hand movements was analyzed.

Soderberg et al investigated the activity of three portions of erector spinae muscles in response to sitting in chairs with inclined seat pans.[10] They evaluated the effects of flat and anteriorly inclined chairs (postures) on the activity of these muscles. The experimental design considered subject-posture, and duration of sitting (time) factors and the posture and time interaction. The experimental design is shown graphically in Figure 7-7. In this study, MVCs of the back musculature solicited with the subject laying in the prone position were recorded and used to normalize the data. Here again, it was assumed that the orientation and length of the muscles of interest would be similar to that observed in the experimental conditions. The root-mean-square (RMS) processed EMG signal was used as the dependent measure in this experiment. Subjects were asked to perform a typing task on a computer terminal during the experiment. This study was different than the previously mentioned studies in that the EMG signal was digitized and recorded on-line with a computer. The normalized data was analyzed using ANOVA and post-hoc techniques. The results were able to determine that different erector spinae muscle activity levels were present during sitting on the various chair designs.

DeGroot used normalized EMG to study the task of postal letter sorting.[11] Three shoulder muscles were evaluated as postal employees sorted mail into a pigeon hole sorting frame. Because this was somewhat a dynamic task, the data first were reviewed and then excluded if they contained motion artifacts. The data was processed using normalized RMS procedures. This data was used to form regression equations that predicted EMG activity as a function of the horizontal and vertical location of the pigeon hole. A statistically significant regression

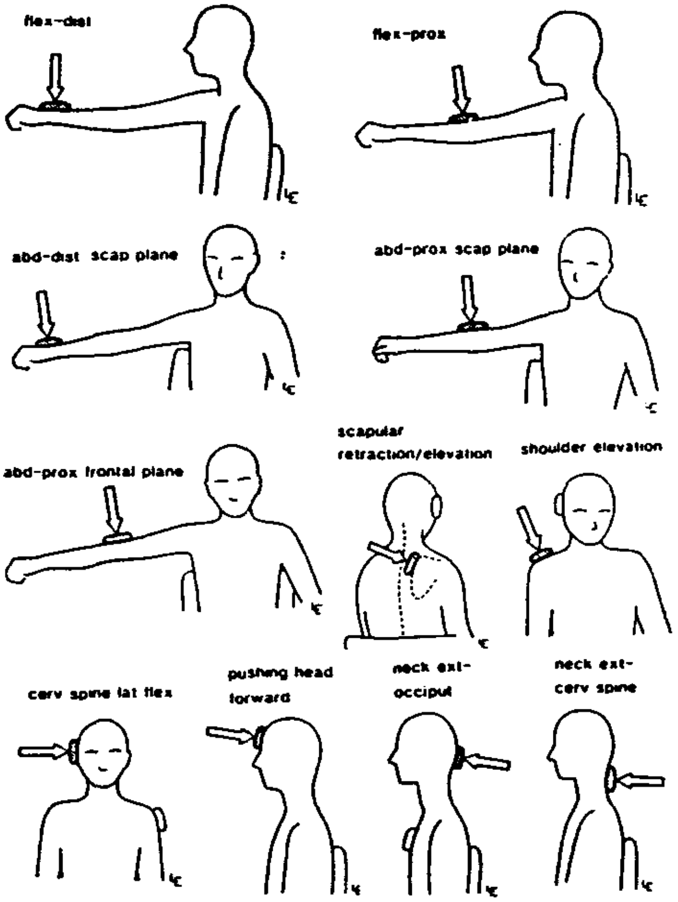

FIGURE 7-4

Isometric test contractions. Arrow to shaded area indicates location of manual resistance. Unfilled area shows point of manual support. For description of test contractions, see their Methods section.

Reprinted with permission from Schuldt K: On neck muscle activity and load reduction in sitting postures: An electromyographic and biomechanical study with applications in ergonomics and rehabilitation. Scand J Rehabil Med [Suppl] 19, 1988, 1-49, Figure 7.

model was developed that was capable of determining the contribution of the various pigeon hole locations to muscle activity. Figure 7-8 illustrates the relationship found between pigeon hole location and muscle activity. This information was used to hypothesize the occurrence of various occupationally related arm-shoulder syndromes. The result was a redesign of the sorting frame used in the postal system.

Next, EMG activity level often is used to evaluate tool design. Rockwell and Marras investigated the effects of the design and method of use of leverage tools on the EMG activity of the back musculature.[12] In this study, a back dynamometer was used to test and control the back position and to solicit isometric MVCs. In this manner, the experimenters were able to match and normalize the back position with that required by the experimental task. The RMS processed EMG signal was used as a dependent measure, being recorded on-line with a microcomputer. Figure 7-9 shows a schematic representation of this equipment. This study also used an ANOVA and post-hoc procedures to evaluate the results. It should be pointed out that even though the tool design was of primary interest in this study, the method of use (in addition to other variables) had to be incorporated into the design so that appropriate comparisons between tool

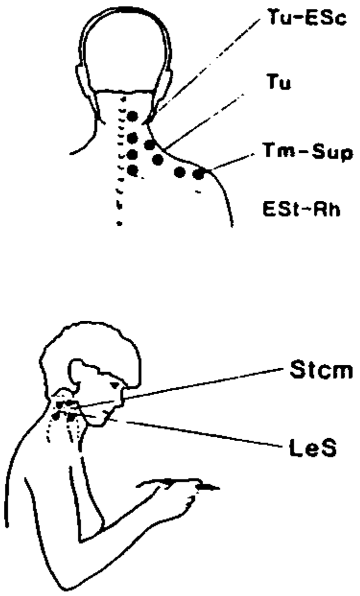

FIGURE 7-5

The location of recording electrodes: Tu-ESc, erector spinae cervicalis covered by upper part of trapezius; Tu, trapezius, pars descendens at anterolateral margin; Tm-Sup, trapezius, pars transversa covering superaspinatus; ESt-Rh, erector spinae thoracalis covered by the rhomboids; Stcm, sternocleidomastoideus; LeS, levator scapulae.

Reprinted with permission from Schuldt K, Ekholm J, Harms-Ringdahl K, et al: Effects of changes in sitting work posture on static neck and shoulder muscle activity. Ergonomics: 29:1525-1537, 1986, Figure 1.

designs could be made.

Finally, the activity levels of muscle are used often in ergonomic studies to help interpret the response of the musculoskeletal system to various work conditions and hazards. Bhattacharya et al used normalized EMG activity to evaluate the level of muscle usage employed during a carpet installation task using a knee-kicker tool.[13] They studied this dynamic task by breaking the dynamic action into four static body postures that represented the components of the dynamic task. These postures and the associated EMG activities are shown in Figure 7-10. They also studied a dynamic carpet installation task using the knee-kicker tool. They recorded the activity of the arm, shoulder, and leg muscles during these static and dynamic activities. The EMG data were normalized by comparing the EMG activity with standard maximum exertions of the muscles. Processing of the static EMG signals was accomplished using a linear envelope procedure. These signals were not compared statistically, so no interactions between experimental main effects v evaluated. The results were subjectively compared by representing the subject data in histograms. The dynamic EMG activity amplitudes were not evaluated because they contained dynamic motion artifacts. However, this information was used to evaluate the percentage of time each muscle group was active. This was accomplished by observing the on-off times of the muscles throughout the cycle of work. This analysis enabled the authors to suggest changes in the method of tool use so that musculoskeletal strain would be minimized.

Another example is provided by Seroussi and Pope who used normalized EMG activity levels to investigate how the trunk muscles responded to lifting moments in the various planes of the body while subjects were in isometric standing positions.[14] The procedures used in this study were similar to those used in the previous two referenced studies; however, in this study the EMG data was normalized according to the equation:

$$\text{Relative Activity} = \frac{\text{Task EMG} - \text{Rest EMG}}{\text{Maximum EMG} - \text{Rest EMG}} \qquad (1)$$

This permitted the investigators to assess the contribution of only the changes in lifting moments in various locations about the body. A similar procedure was used by Marras et al to investigate the reaction of the musculoskeletal system to unexpected load handling.[15] In this study, the EMG activity of 6 trunk muscles were normalized by equation (1). The task of interest required the subject to stand in an isometric posture and hold a box into which weights were dropped under expected and unexpected conditions. Analysis of variance procedures were used to evaluate the peak, mean, and onset rate parameters of the EMG activity under the various expectation conditions. The parts of the EMG that were evaluated are identified in Figure 7-11. In this manner, the change was documented in the activity parameters of the trunk muscles resulting from load increase and expectation. Based on these EMG activity level analyses, adjustments to lifting guidelines for specific work place conditions were recommended.

Muscle Usage Through Microvolt Activity Level

Ergonomic studies can also be found in the literature that investigate muscle usage based solely on the amount of microvolts of EMG activity observed during a work task. The only difference between these studies and those that measure normalized activity level is that these studies usually do not test each subject's MVC of the muscle. Therefore, a different baseline of EMG activity sensitivity may be recorded with each subject unless precautions are taken. This different baseline is due to varying levels of

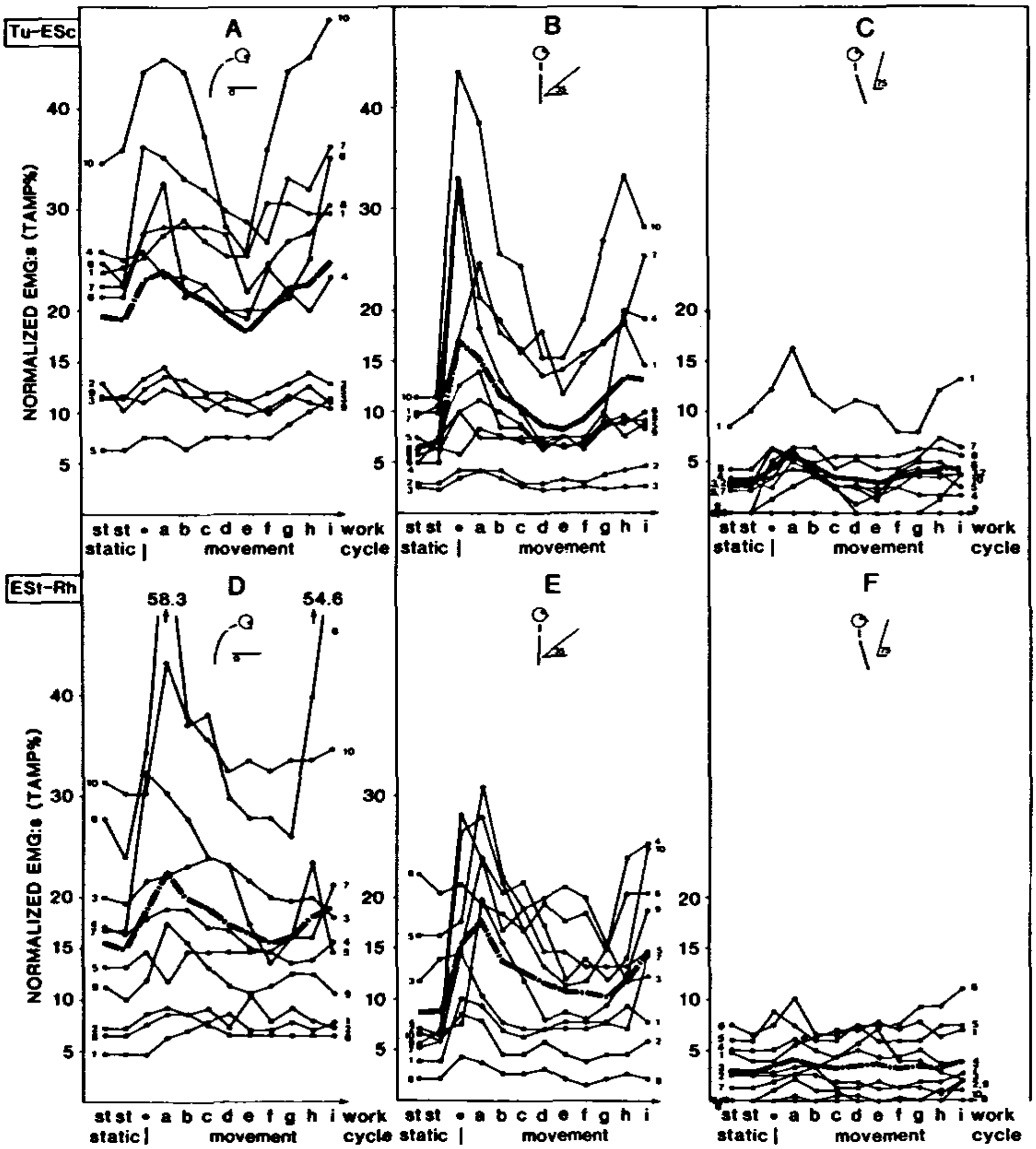

FIGURE 7-6

Level of muscular activity (vertical axis, TAMP%) in relation to course of simulated work cycle (horizontal axis), starting with last part of static phase and continuing with movement phase with arm-hand moving from position 'a' to 'b', etc, and back to 'i'. Thick segmented lines indicate means. Differences between three sitting postures also illustrated. A,D: gives the posture WFHO as indicated at the top of the figure; B,E: gives the WV; C,F: gives the TLBCV posture. Small numerals indicating subjects are shown at the beginning and end of each curve. For explanation of abbreviations, see their Methods section and Figures 1 and 3. (n = 10)

Reprinted with permission from Schuldt K, Ekholm J, Harms-Ringdahl K, et al: Influence of sitting work postures on neck and shoulder EMG during arm-hand work movements. Clin Biomech 2:126-139, 1987, Figure 4, p 130.

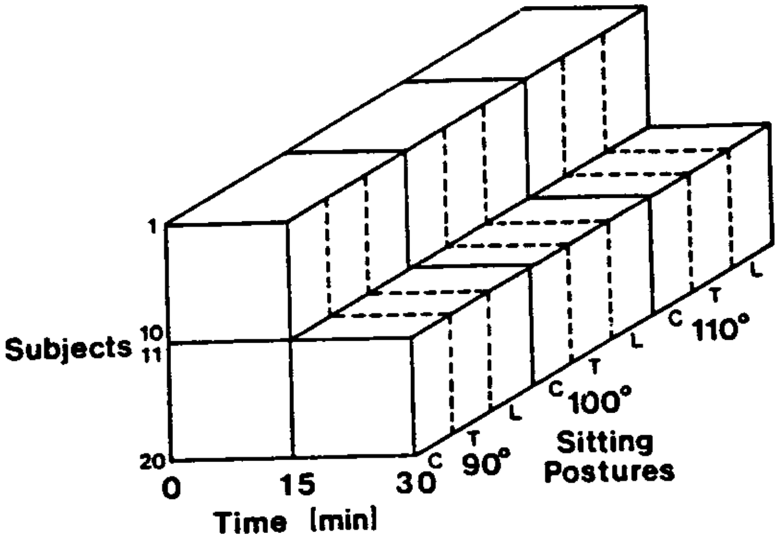

FIGURE 7-7
Graphic representation of the multifactoral repeated measures design of the study. Cervical (C), thoracic (T), and lumbar (L) segments are represented at each posture.

Reprinted with permission from Soderberg GL, Blanco MK, Cosentino TL, et al: An EMG analysis of posterior trunk musculature during flat and anteriorly inclined sitting. Human Factors 28:483-491, 1986, Figure 2.

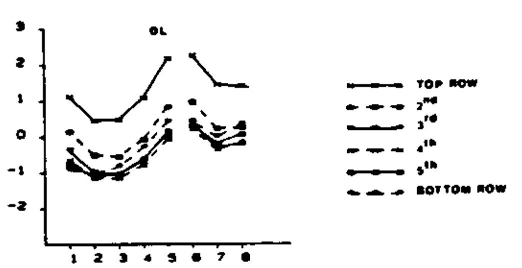

FIGURE 7-8
Normalized value of EMG activity averaged over subjects.

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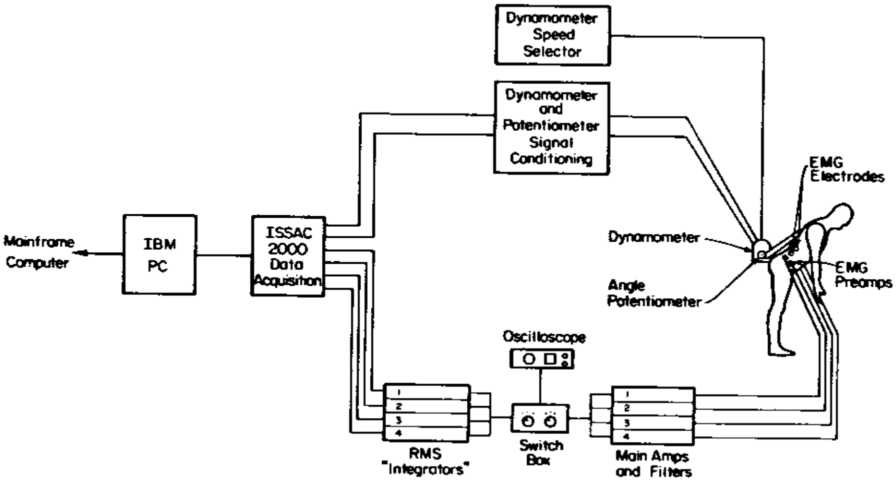

FIGURE 7-9

The experimental apparatus.

Reprinted with permission from Rockwell TH, Marras WS: An evaluation of tool design and method use of railroad leverage tools on back stress and tool performance. Human Factors 28:303-315, 1986, Figure 1.

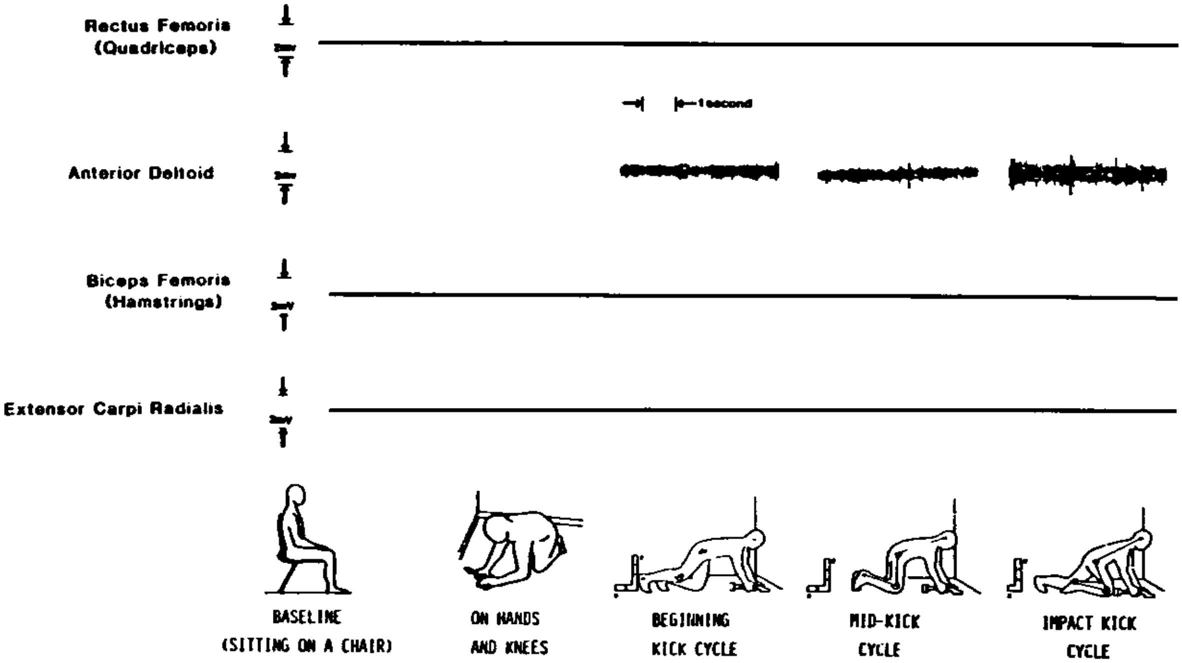

FIGURE 7-10

Raw EMG data associated with static postures of carpet installation task.

Reprinted with permission from Bhattacharya A, Ramakrishanan HK, Habes D: Electromyographic patterns associated with a carpet installation task. Ergonomics: 29:1073-1084, 1986, Figure 4, p 1079.

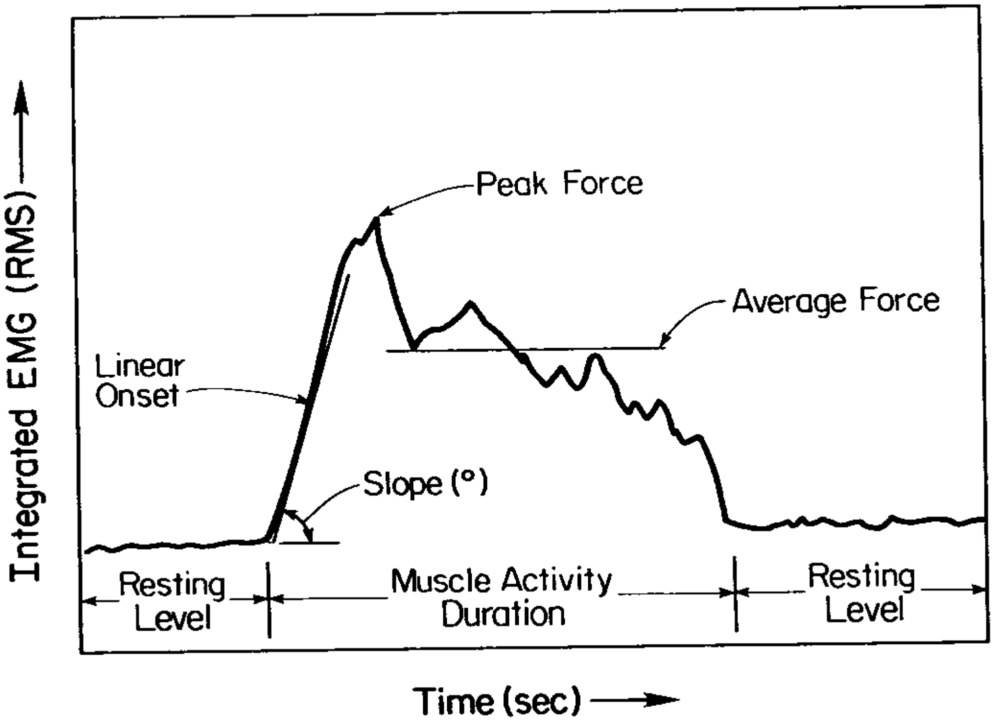

FIGURE 7-11

Trunk muscle activity components used in analysis.

Reprinted with permission from Marras WS, Rangarajulu SL, Lavender SA: Trunk loading and expectation. Ergonomics: 30:551-562, 1987, Figure 2, p 556.

electrode impedance and varying levels of subcutaneous tissue between subjects. The important element in successfully recording activity level by this method is precise calibration of the EMG signal. It is imperative to determine precisely the gain of the EMG system with this method. This is done usually by adjusting the gain of the system so it is within the most sensitive range of the recording system (eg, chart, FM recorder, computer). Then a known calibration signal is provided as input and recorded. Thus, the gain is known precisely. This methodology in ergonomic investigation often limits use of more sophisticated statistical analysis techniques. Because few assumptions about the distribution of the EMG signal can be made and intervariability is not well controlled, the statistical analyses usually are limited to comparisons between mean activities. These tests often are not as powerful as tests based on variance.

As with normalized activity level investigations, these studies usually involve investigations of work methods, environments, or the response of the musculoskeletal system to work place conditions. Several examples will be mentioned here.

Andersson and Ortengren used this method to evaluate loads on the backs of workers in an automobile assembly plant under several work situations.[16] In this study, the EMG signal gains were calibrated individually for each muscle periodically throughout the testing period. During the calibration, workers were asked to maintain a specified posture while holding known weights in the hands. The EMG signals were hard wired to an FM tape recorder for permanent recording. The RMS processed EMG signals were evaluated by representing the data in amplitude histograms. In this method the amplitude of the signal was divided into 5 intervals, and the time spent in each of the intervals during a task was divided by the total period of measurement and multiplied by 100. This interval analysis is portrayed in Figure 7-12. In this manner, the muscle amplitude was represented in microvolts, but the amount of time spent in each interval was normalized. Thus, the temporal aspects of EMG

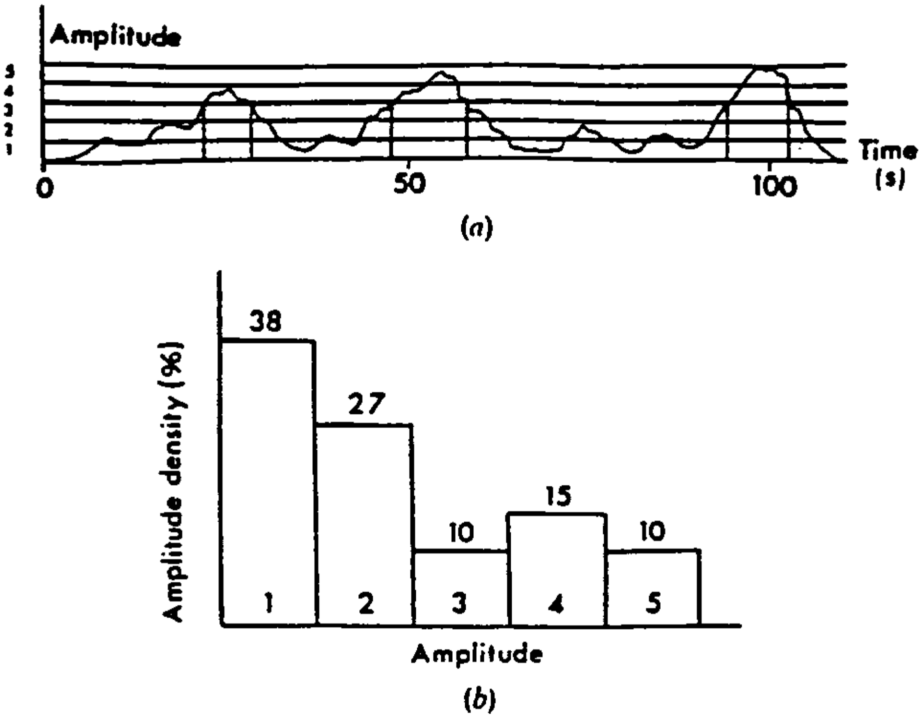

FIGURE 7-12

(a) Example of myoelectric signal amplitude variations during a work spell. The curve is obtained after full-wave rectification and low-pass filtering of the raw myoelectric signal. Five amplitude intervals are marked. (b) Amplitude histogram showing the total time the amplitude curve in (a) spends in each interval in percentage of the total recording time (amplitude density diagram).

Reprinted with permission from Andersson GBJ, Orgengren R: Assessment of back load in assemblyline work using electromyography. Ergonomics 27:1157-1168, 1984, Figure 4.

activity were normalized but not the activity amplitude. This permitted the investigators to plot histograms as a function of tasks and workers. Statistical analyses consisted of a report of mean values, standard deviations, and confidence intervals. Through this analysis technique, the investigators were able to evaluate the relative back load associated with assembly tasks and quantify the degree of load relief offered by lifting aids.

Andersson et al used EMG microvolt activity as a dependent measure to study sitting as a function of 1) chair angle and lumbar support, 2) office chairs while performing office tasks, 3) tasks performed in a wheelchair, and 4) chair variables as a function of driving maneuvers, respectively.[17,20] In each one of these studies, three to four subjects were evaluated under the experimental conditions. Data were recorded on an FM tape recorder for later analyses. In these studies, calibration was performed by recording sine waves of known amplitude after each investigation. In this manner, the exact gain was determined for each muscle. The recordings were played back through an ink chart recorder after the signals were processed using RMS circuitry. These values were visually read and entered into a computer for statistical testing. The EMG means, standard deviations, and confidence intervals were computed, and statistical t-tests were performed to determine the statistically significant differences between the means. Figure 7-13 shows the mean and standard deviation of the unnormalized EMG data collected in this experiment. These studies indicate how direct readings of microvolt EMG levels may be used to evaluate the effects of seat induced postures and task requirements in a work place. There were restrictions in making comparisons between subjects because the data were not normalized; therefore, higher order analyses of the variances and interactions were not analyzed.

Andersson et al have also used microvolt activity levels as a means to investigate the effects of posture and loading on the muscle activity of different parts of the

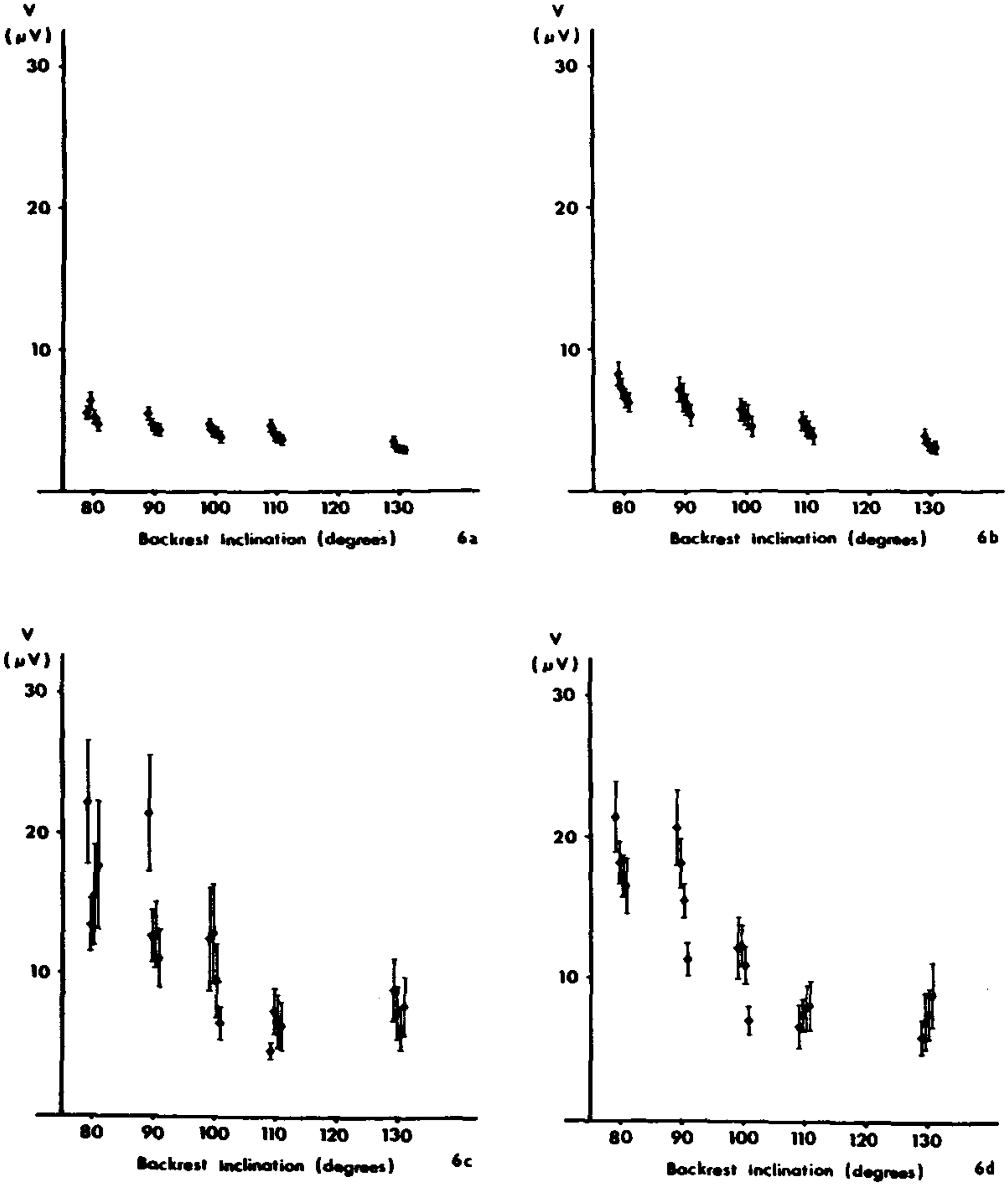

FIGURE 7-13
Mean FRA values and standard deviations of the means. Thoracic support 0 degrees. At each backrest inclination four values are given: From left to right -2, 0, +2 and +4 cm of lumbar support. The recordings were made from the left side of the trunk. (a) C4 level, (b) T1 level, (c) T3 level, (d) T8 level.

Reprinted with permission from Andersson GBJ, Orgengren R: Myoelectric back muscle activity during sitting. Scand J Rehabil Med [Suppl] 3:73-90, 1974, Figure 6.

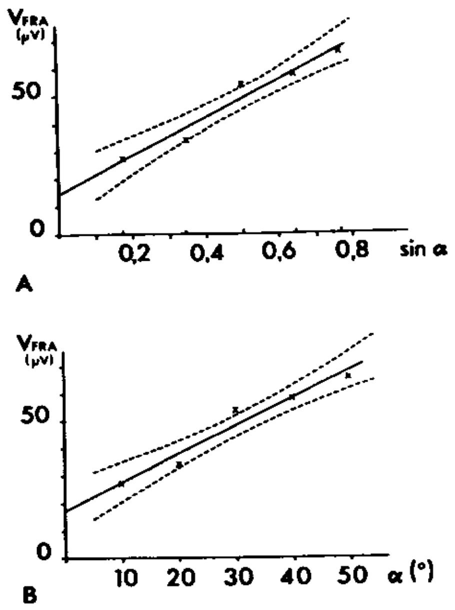

FIGURE 7-14

Linear regression lines for the relationship between the myoelectric activity at the L 3 level. (A) the sine of the angle of forward flexion, and (B) the angle of flexion. Ninety-five percent confidence regions are indicated.

Reprinted with permission from Andersson GBJ, Orgengren R, Herberts P: Quantitative electromyographic studies of back muscle activity related to posture and loading. Orthop Clin North Am 8:85-96, 1977, Figure 4, p 89.

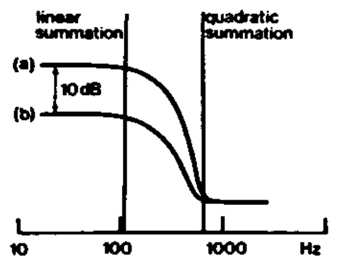

FIGURE 7-15

The total EMG output in microvolts, given a certain number of contracting fibers per unit time, depends on the motor unit size: (a) one motor unit with 500 fibers, (b) 10 units with 50 fibers each. The frequency dependence is due to the fact that low-frequency components appear in synchrony within the motor unit, whereas in the high-frequency range, all components appear at random regardless if the signal is produced by one or several motor units.

Reprinted with permission from Kadefors R: Application of electromyography in ergonomics: New vistas. Scand J Rehabil Med 10:127-133, 1978, Figure 2, p 128.

back.[21] Here, the absolute level of EMG activity was used again, and the analyses consisted of a regression analysis so that the relationship (correlation) between trunk angle, load, and EMG activity could be assessed. Figure 7-14 shows this relationship.

Muscle Force Through Normalization

As discussed in Chapter 5 as well as earlier in this chapter, it has been well established that under certain controlled conditions a known relationship (often linear) exists between muscle force and processed EMG. The literature indicates that muscle force estimates are derived usually by using either normalized EMG or the microvolt level of activity as an indication of muscle usage and force. This section will focus on the more widely used approach of normalization.

Regardless of the EMG relationship used to predict force, several conditions must be satisfied to derive muscle force. First, the muscle of interest must be in a static or controlled dynamic state. This is controlled usually through the experimental design and methodology. Second, the EMG-force relationship must be qualified according to the unique properties of the muscle (see Chapters 2 and 6) and is represented usually by a functional relationship or a model. Finally, it is of utmost importance to ensure that a given portion of the muscle is sampled because factors such as the length-tension relationship of the muscle may confound the EMG-force relationship. Only under these conditions can one make statements about the relative amount of force in a muscle during different work conditions often of interest in ergonomic studies.

Gagnon et al used the percentage of maximum EMG as the means to assess muscle force present while nurses aids lifted patients using three different methods.[22] As with other predictions of muscle force, this study also used a mathematical model to interpret the EMG activity relative to muscle force and back loading. The model consisted of a static and planer mathematical model that used EMG and force plate data to assess the forces acting on the spine. This study required the subjects to execute three isometric MVCs that served as a reference level of EMG activity for comparison. These authors, as well as Basmajian and DeLuca,[23] advocate such a normalization procedure because it permits more accurate comparisons between subjects and muscle groups. Though these investigators did not compute correlation coefficients between predicted muscle force and measured EMG activity, they found that the pattern of activation within the erector spinae muscles did follow the pattern of compressive forces predicted by the model. This study is unique in that it used EMG recordings to predict muscle force under uncontrolled dynamic motion.

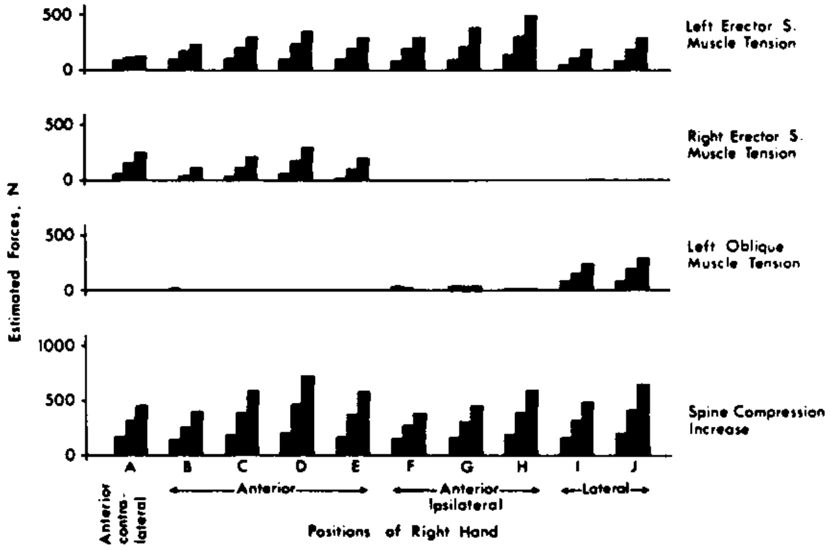

FIGURE 7-16

Muscle tensions and compression increase on the spine predicted from the analysis. The three levels on each bar, from left to right, correspond to the weights held (0, 40, and 80 N).

Reprinted with permission from Andersson GBJ, Orgengren R, Schultz A: Analysis and measurement of the loads on the lumbar spine during work at a table. J Biomech 13:513-520, 1980, Figure 4, p 518.

Based on this investigation, the authors were able to distinguish back loading using the different methods and were able to identify the best method of patient lifting.

Marras used a percentage of maximum EMG in conjunction with a mathematical model to estimate the muscle tension present during isometric and isokinetic (constant velocity) lifting motions in the back of 20 male and female subjects.[24] The lifting velocities varied from very slow to very fast. The correlation coefficient between the predicted muscle tension and normalized EMG activity of the erector spinae muscles under all conditions was weak (.37) but statistically significant.

Reilly and Marras used normalized EMG activity as input to a biomechanical simulation model that was used to predict spine compression and shear forces during lifting motions.[3] The EMG signals were used to indicate the relative force in the muscles in each lifting condition. These motions also were isokinetically controlled, making it possible to evaluate the impulse loading on the spine resulting from the coactivation of the trunk musculature.

These studies indicate that the percentage of EMG activity can be used to predict the tension within muscles during occupational tasks. This technique has the advantage of allowing comparisons between subjects and muscle groups. It also is important to recognize that the EMG-muscle tension relationship is not as well defined and seldom used to evaluate muscle force during ballistic motions.

Muscle Force Through Microvolts

Many researchers have attempted to investigate the force of a muscle by simply observing the rectified and averaged (in some cases integrated) EMG signal in terms of the absolute number of microvolts generated and associated with a particular activity. However, there are two difficulties with attempting to assess muscle force by this method. First, EMG is capable of only assessing the activity of the portion of the muscle from which the electrodes are recording activity. Hence, the determination of muscle force is not technically possible. The derived parameter of muscle tension, however, can be determined as force per unit cross-section area. The problem occurs when trying to relate a given volume of muscle to the EMG activity level. If surface electrodes are used, the electrodes reside at some unknown (and sometimes varying) distance from the muscle. Furthermore, the uptake

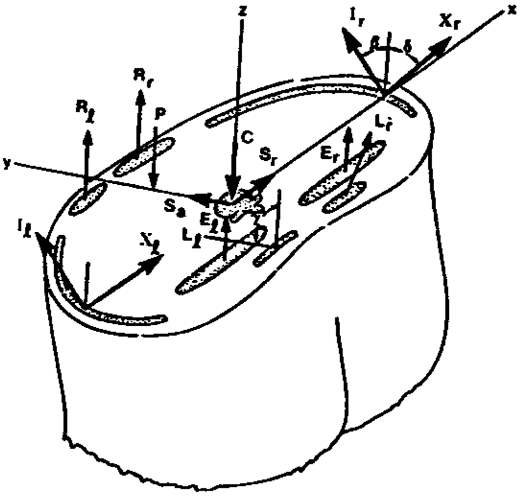

FIGURE 7-17

Schematic of the model used for internal force estimation. The five bilateral pairs of single muscle equivalents represent the rectus abdominis, the internal and external oblique abdominal, the erector spinae, and those parts of the latissimus dorsi muscles that cut the trunk sectioning plane. Contraction forces in these model muscles are denoted R, I, X, E, and L, respectively, with the subscripts denoting left and right sides. Inclination angles, *β*, *d*, and y were all set to 45 degrees. Motion segment compression force is denoted C, anterior shear force S_a, and right lateral shear force S_r. Abdominal cavity pressure resultant P here was set to zero. Muscle cross-sectional area per side were taken as, respectively, for R, I, X, E, and L: 0.006, 0.0168, 0.0148, 0.0389, and 0.0037 times the product of trunk cross-section depth and width. Centroidal offsets in the anteroposterior direction were, in the same order, taken as 0.54, 0.19, 0.19, 0.22, and 0.28 times trunk depth. In the lateral direction, they were taken as 0.12, 0.45, 0.45, 0.18, and 0.21 times trunk width.

Reprinted with permission from Schuldt K. Andersson GBJ, Haderspeck K, et al, Analysis and measurement of lumbar trunk loads in tasks involving bends and twists. J. Biomesh 15:669-675, 1982, Figure 1, p 671.

volume of EMG activity will be a function of the frequency and may not be consistent between muscles. This problem can be corrected only with certain indwelling electrodes where the electrode geometry is well defined.[25]

The second problem in relating EMG microvolt level to muscle tension relates to basic differences in the anatomical construction of the muscles. Intervation ratios associated with muscles vary greatly depending on the amount of fine control or power associated with a muscle. Thus, even if a given number of fibers per cross-sectional area of muscle were active, the microvolt reading in different muscles would be different. This is because up to a certain frequency, the electrical activity of fibers belonging to the same motor unit sum linearly. Fiber potentials of different motor units, however, add in square.[26] This is shown in Figure 7-15. This means that in muscle with large motor units, a certain number of activated fibers will result in a greater microvolt reading than a muscle composed of smaller motorunits.

The ergonomist, therefore, would have difficulty, in most cases, in determining force or even tension based on the absolute microvolt activity of an integrated EMG signal. Those who have attempted to do so have used EMG in conjunction with a biomechanical model to evaluate this relationship. Andersson et al used a biomechanical model that considered the cross-sectional geometry of the trunk to evaluate the moments generated by the erector spinae muscles within the trunk.[27] This model was used to assess tasks that involve static submaximal arm lifts while working at a table. The EMG signal gains were calibrated with the wave calibration technique discussed earlier so that the signal amplitudes could be expressed in microvolts. These researchers used anthropometric information relating the mass center of the arm complex and the moment arm from the vertebral body to estimate the moment that must be resisted by the muscles to maintain a state of static equilibrium. They also assumed there was no antagonistic muscle activity present in the task. Figure 7-16 shows the predicted force generated by each muscle as a function of the experimental conditions. This study reported correlation coefficients between muscle tension and EMG activity of .99 and .98 for the right and left sides of the body, respectively.

Schultz et al used a similar method to evaluate the muscle tension in 10 trunk muscles in tasks involving static 15-second duration bending and twisting positions while holding weights that varied in magnitude between 4 and 20 kg.[28] In this study, the evaluation used a biomechanical model that considered the moment arm between the spine and the trunk muscles and the cross-sectional area of those muscles. This relationship is shown in Figure 7-17. Here again, no muscle activity from antagonists were included in the model. Depending on the method used to solve the biomechanical model, the correlation coefficients between the predicted muscle tension and the RMS processed EMG signal ranged from .34 to .92. A latter study by Zetterberg et al used a similar model to predict trunk muscle tension while exerting maximal and 50% of maximal isometric trunk force.[29] This model differed in that it allowed for antagonistic activity of the trunk muscles. The correlation between predicted muscle tension and the RMS processed EMG signal amplitudes improved for most of the back musculature. This relationship is shown for two of the muscles investigated in Figure 7-18.

Andersson et al used a unique microvolt calibration scheme to evaluate the forces acting on the trunk while subjects performed three common tasks at a table.[30] In this study, the EMG activity of the muscles was correlated with muscle force through a series of calibration experiments. Subjects were seated in the same position as required during the experimental task and were asked to hold weights of different magnitudes in different static positions on a table. Regression analysis was used to establish EMG-force relationships. The authors believed that this was a better way to establish this relationship than by normalizing the EMG activity. This information was used as input into a biomechanical model so that the forces on the lumbar spine could be determined. The model, however, did not consider coactivation of the trunk musculature. The authors concluded that spine loading generally was low in this type of work and that load levels were influenced only marginally by work place factors such as table and chair adjustments even though these factors were not included in the experimental design or statistically evaluated.

A similar task was evaluated by Boudrifa and Davies.[31] They investigated the integrated EMG microvolt activity of the erector spinae muscles while subjects lifted a 10 kg weight on a table located at different angular locations and different distances from the body. They evaluated the results with ANOVA and determined that the lifting distance and the interaction of distance with angle were significant; the angle factor was not. When the results of this study are compared with those of the previous study, the importance of including a complete experimental design and statistically evaluating the EMG data are evident.

These studies emphasize several issues in the use of microvolts of EMG activity to predict muscle force. First, all of these studies have assumed a linear relationship between muscle force and EMG activity. Second, to evaluate the muscle force relationship, all have used EMG in conjunction with a biomechanical model. Most of these investigations have used models based on moment relations and the cross-sectional area of the muscle. Third, all of the tasks evaluated have been static. This condition preserves the length-tension relationship in the muscle. Finally, when the tasks evaluated involved increased force exertions, the inclusion of antagonistic coactivation of muscles improved predictability of the muscle forces. In summary, it is not a simple task to estimate muscle tension by this method. If this method is used, it must be done with careful calibration and an appropriate biomechanical model.

Muscle Fatigue

Muscle fatigue can be evaluated either by observing the change in amplitude of the EMG signal through the microvolt level or by observing the change in the spectral activity of the signal. The latter is appearing now more frequently in the literature and appears to be a powerful investigative tool. Details of this technique have been presented in previous chapters. Examples of both these approaches follow.

Muscle Fatigue Through Microvolts

As early as 1912, Piper demonstrated that as a muscle fatigues, the EMG signal will increase in its amplitude while the muscle is exerting a given amount of force in an isometric contraction.[32] This probably is due to the need to recruit more motor units to perform the same amount of work as the muscle fibers fatigue. Thus, by observing the processed EMG signal of a given portion of the muscle under constant force conditions, a quantitative indicator of the degree of muscle fatigue can be established. It also is important to note that this trend is evident only with surface electrodes. Unfortunately, simultaneous isometric and isotonic contractions are seen rarely in ergonomic studies. Thus, the use of this method of assessment usually is limited to comparisons of prework and postwork test conditions to determine if increased EMG activity is required to exert a given force. It is presumed that increased EMG activity would be attributable to the task that preceded the post-test. The flaw in this approach, however, is that even a slight change in EMG activity resulting from minute muscle loading changes would signal a change in fatigue status.

Habes used this approach to evaluate the securing of material to two types of dies in an automobile upholstery plant.[33] Electrodes were placed on the low back muscles, and the EMG signals were transmitted using

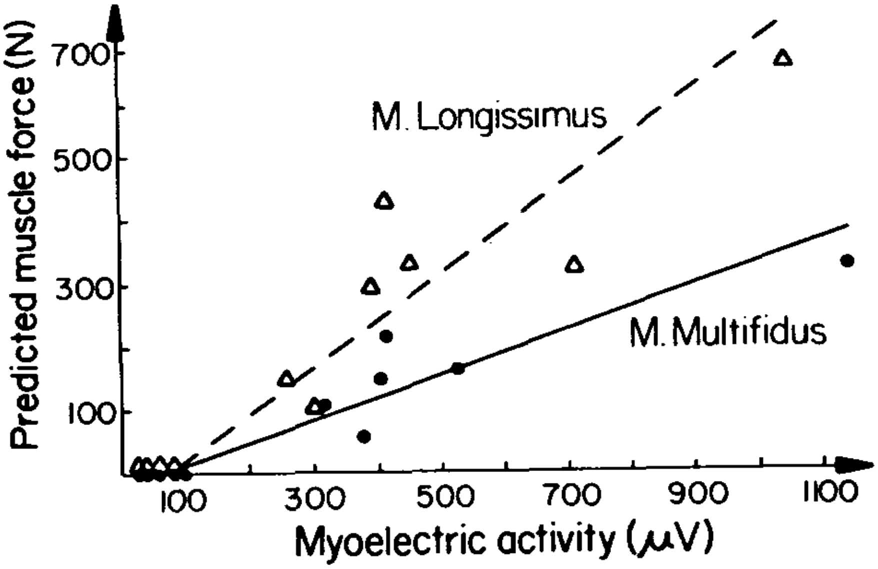

FIGURE 7-18

Relationship of mean myoelectric activities and predicted muscle forces for the longissimus and multifidus parts of the erector spinae muscles.

Reprinted with permission from Zetterberg C, Andersson GBJ, Schultz A: The activity of individual trunk muscles during heavy physical loading. Spine 12:1035-1040, 1987, Figure 1, p 1039.

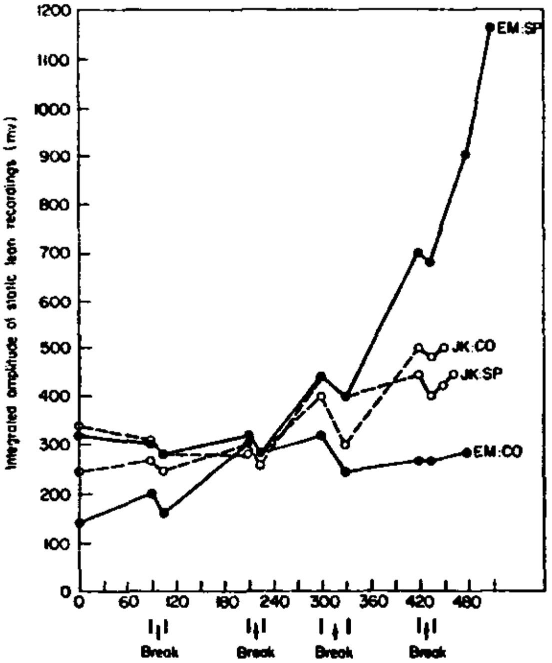

FIGURE 7-19

Static lean fatigue curves.

Reprinted with permission from Habes DJ: Use of EMG in a kinesiological study in industry. Applied Ergonomics: 15:297-301, 1984, Figure 4.

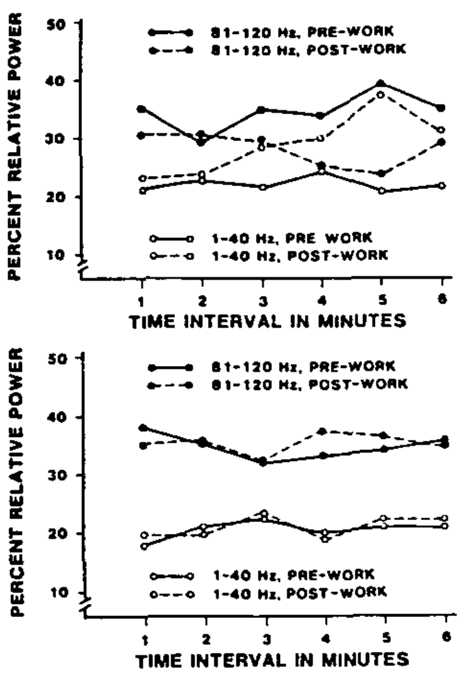

FIGURE 7-20

Average percentage of relative power in the low- and high-frequency bands of EMG activity recorded from the flexors during prework and postwork keyboard operation. These data, presented as a function of increasing time, were recorded from operators entering predominantly four-digit destination codes to sort box mail (upper graph) and from operators entering predominantly three-digit destination codes to sort outgoing primary mail (lower graph).

Reprinted with permission from Gomer FE, Silverstein LD, Berg WK, et al: Changes in electromyographic activity associated with occupational stress and poor performance in the workplace. Human Factors 29:131-143, 1987, Figure 4.

telemetry to an FM tape recorder. In this manner, two subjects were tested throughout the work day without interfering with their work schedule. The experiment required subjects to maintain a 5-second test posture at 10 different times throughout the work day while the microvolt EMG activity necessary to maintain that posture was recorded. This study was able to identify dramatic increases in EMG activity associated with the use of one of the dies that was not identified when other measures of muscle fatigue were evaluated. An example of how the EMG increased over time is shown in Figure 7-19.

Christensen performed a similar type of study on 25 assembly line workers.[34] The goal of the study was to assess the level of fatigue in the shoulder muscles of employees throughout the work day. The subjects were tested at eight times during the day, each for a 10-minute period while they performed their normal job. The EMG activity was represented by an amplitude probability function. Even though subjective questionnaires indicated that the subjects were experiencing fatigue throughout the day, the EMG activity levels did not indicate a fatiguing situation. These results may have been due to the lack of a standard test contraction in the experimental design.

Muscle Fatigue Through Spectral Analysis

One way to minimize the interactive effect of muscle force on fatigue is to analyze the spectral components of the EMG signal. It is known that as the muscle fatigues, the high frequency components of the signal diminish. This spectral shift resulting from fatigue is a first-order effect in the signal spectrum, whereas, moderate changes in the contraction level of the muscle cause second-order effects in the signal spectrum. Thus, an objective measure that is not as affected by muscle contraction irregularities is that of observing the frequency shift of an EMG signal during a static exertion. This shift usually is observed by using a fast Fourier transform (FFT) to change the raw EMG signal from the time domain to the frequency domain. Once this is done, center frequency, or median frequency, estimates are used to indicate the central tendency of the EMG spectrum. This usually is done in a manner similar to the microvolt approach in that comparisons of these factors usually are made before and after a work period during a test contraction at a given level of muscular contraction. The spectral components, however, are not as sensitive to minor deviations in muscle force levels. Several authors have described how a shift in the center frequency to a lower value can indicate a fatigued state of the muscle.[35-37]

Gomer et al used spectral analyses of the EMG signal to evaluate fatigue in the forearms of mail sorters who performed a machine-paced keyboard operation.[38] They evaluated two different work practices associated with the keyboard operation. In this study, 20 experienced mail sorters were tested with a prework and postwork test exertion. These exertions required the subject to exert maximal grip strength on a grip dynamometer for 30 seconds. The relative power in the lower frequency portion (1-40 Hz) of the EMG spectrum was compared with the power in the upper portion (81-120 Hz) of the spectrum during the pre-tests and post-tests. Figure 7-20 shows a comparison of these portions of the EMG spectrum as a function of the experimental conditions. The relative power shifts were evaluated by a multifactor ANOVA design that enabled the investigators to determine which work place factors contributed to fatigue during the shift. The results clearly showed that one of the work practices was superior.

Similar techniques can also be used to assess the design of tools and work orientation used in the work place. Schoenmarklin and Marras also used a pre-test and post-test procedure to evaluate arm fatigue associated with the design and use of a hammer.[39] In this study, however, the test contractions consisted of hand grip contractions that were 70% of the maximum voluntary grip contraction. They hypothesized that if the subjects fatigued during the test, they would not be able to reachieve the original 100% force level. This level of contraction was controlled by having the subjects match a target on an oscilloscope that represented the 70% exertion for each subject. In this study, the median frequency of the signal was compared before and after each trial. The results were analyzed by an ANOVA procedure that was able to assess the fatigue effects resulting from the experimental factors and their interaction. In this manner, they were able to determine the contribution of tool design and tool use orientation on the fatigue of the muscle.

It should also be pointed out that some researchers use both the microvolt method and the spectral analysis methods simultaneously to indicate fatigue in a muscle. In the study performed by Habes[33] mentioned earlier, for example, the percentage of EMG signal power in the 4 to 30 Hz frequency band was evaluated during the 10 static test postures. The percentage of power in this low frequency band was compared with the fatigue indicating criteria set forth by Chaffin.[36] Although the increases in back EMG activity throughout the day were interpreted as a sign of fatigue, none of the power frequency shifts exceeded a predetermined minimum level considered necessary to indicate fatigue.

SUMMARY

The use of EMG in ergonomic investigations is not a technique that should be applied indiscriminately. Planning for the experimental or functional question to be answered is important. Furthermore, proper signal collection and analysis procedures must be used if useful information is desired. Several key steps must be considered when applying EMG in an ergonomic investigation. First, before EMG is used, the experimenter must have an idea about which muscles would be affected by the work and the type of information about the muscle that is desired (duration/on-off, force, or fatigue). Second, the experimental design should consider all factors that may affect muscle use (i.e. work place layout, work method, etc). Third, those variables that may affect the EMG signal (motion, pick up area, etc.) should be controlled in the experiment. Fourth, the best available means of signal treatment and processing should be selected. The EMG relationships of interest and their limitations, as detailed in this manual, must be considered when selecting the proper EMG treatment and processing technique. Finally, proper statistical analyses should be performed so that the maximum useful information can be extracted from the experiment.

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