CHAPTER 6

Conscious Control and Training of Motor Units and Biofeedback

Studies of neuromuscular and spinal cord function have been growing increasingly complex in recent years without offering clearer answers to many fundamental problems. Especially confusing and fragmentary are theories on the influence of various cortical and subcortical areas on spinal motor neurons and motor units in man. It was therefore refreshing to be able to develop and advocate a technique that not only proved to be quite simple but also promised to reveal considerable fundamental information. Ironically, the technique was only a modification of ordinary electromyography. This modification consists of regarding EMG signals not for their own intrinsic value but as the direct mirroring of the activity of spinal motor neurons. Thus the group of muscle fibers in a motor unit is considered only as a convenient transducer that reveals the function of the nerve cell.

Perhaps the ultimate irony is that in their classic paper establishing the modern era of electromyography in 1929, Adrian and Bronk suggested that ". . . The electrical responses in the individual muscle fibres should give just as accurate a measure of the nerve fibre frequency as the record made from the nerve itself." Even earlier, Gasser and Newcomer (1921) had shown that "the electromyogram is a fairly accurate copy of the electroneurogram." Perhaps as a reflection of the general turning away from man as an experimental animal in favor of more exotic beasts and preparations, no real use of these early conclusions had been made. In fact, the implications in Gasser and Newcomer's work did not lead to any systematic use of electromyography for studying the behavior of individual spinal motor neurons in any species, even though a MUAP reflects the activity of its spinal motor neuron.

No great progress was made until 1928 and 1929, when Adrian and Bronk published two classic papers on the impulses in single fibers of motor nerves in experimental animals and man. Their method consisted of cutting through all but one of the active fibers of various nerves and recording the action currents from that one fiber. They also succeeded in making records directly from the muscles supplied by such nerves. Somewhat incidentally, Adrian and Bronk introduced the use of concentric needle electrodes with which the activity of muscle fibers in normal human muscles could be recorded. Meanwhile Sherrington (1929) and his colleagues had crystallized their definition of a motor unit as "an individual motor nerve together with the bunch of muscle-fibres it activates." (Universally, later workers have also included in their definition the cell body of the neuron from which the nerve fiber arises.)

Although in subsequent years the concentric needle electrode was seized upon for extensive use, until the Second World War only a handful of papers appeared on the characteristics of action potentials from single motor units in voluntary contraction. In 1934, Olive Smith reported her observations on individual motor unit potentials, their general behavior, and their frequencies. She showed that normally there is no proper or inherent rhythm acting as a limiting factor in the activity of muscle fibers; rather, the muscle fibers in a normal motor unit simply respond to each impulse they receive. Confirming earlier work of Denny-Brown (1929) she set at rest the false hypothesis of Forbes (1922) that the muscle fibers or motor units were fatiguable at the rates they were called upon to reproduce by their nerve impulses.

Forbes had also suggested that normal sustained contraction requires rotation of activity among quickly fatiguing muscle fibers. Smith proved that such a rotation need not occur and that an increase in contraction of a whole muscle involves both an increase in the firing rate of impulses in the individual unit and an accession of new units which are independent in their rhythms. The rates ranged from 5 to 7 pps to 19 to 20 pps, although "highly irregular discharge may occur at threshold both during the onset of a contraction and during the last part of relaxation." Finally, she proved that tonic contraction of motor units in normal mammalian skeletal muscle fiber, the existence of which was widely debated, does not exist. Three generations later, there are people in muscle research still not aware of her definitive studies.

Lindsley (1935), working in the same physiology laboratory as Smith, determined the ultimate range of motor unit rates during normal voluntary contractions. Although others must have been aware of the phenomenon, he seems to have been the first to emphasize that at rest "subjects can relax a muscle so completely that . . . no active units are found. Relaxation sometimes requires conscious effort and in some cases special training."

In none of his subjects was "the complete relaxation of a muscle difficult." Since then, this finding has been confirmed and refined by hundreds of investigators, using much more sophisticated apparatus and techniques than those available in the early 1930s.

Lindsley also reported that individual motor units usually began to respond regularly at rates of 5 to 10 pps during the weakest voluntary contractions possible and some could be fired as slow as 3 pps. The upper limit of firing rates was usually about 20 to 30 pps but occasionally was as high as 50 pps. Earlier, Adrian and Bronk (1928, 1929) had found the same upper limit of about 50 pps for the nerve impulses in single fibers of the phrenic nerve and from the diaphragm of the same preparations.

Gilson and Mills (1940, 1941), recording from single motor units under voluntary control, reported that discrete, slight, and brief voluntary efforts may call upon only a single potential (i.e., a single twitch) of a motor unit being recorded. Twenty years later, Harrison and Mortensen (1962) showed that by means of surface and needle electrodes action potentials of single motor units could be identified and followed during slight voluntary contractions in tibialis anterior. Subjects provided with auditory and visual cues could produce "single, double and quadruple contractions of single motor units . . ." and in one case, ". . . the subject was able to demonstrate predetermined patterns of contraction in four of the six isolated motor units."

Using special indwelling wire electrodes, Basmajian (1963) confirmed these findings and on this basis was able to elaborate techniques for studying the fine control of the spinal motor neurons, especially their training, and the effects of volition. Later, in a series of studies, his group further developed and described a system of testing and of motor unit training. They demonstrated the existence of a very fine conscious control of pathways to single spinal motor neurons (Basmajian et al., 1965). Not only can human subjects fire single neurons with no overflow (or perhaps more correctly, with an active suppression or inhibition of neighbors), but also they can produce deliberate changes in the rate of firing. Most persons can do this if they are provided with aural (and visual) cues from their muscles. Many investigators have documented the qualitative and quantitative aspects (for example: Simard, 1969; Zappalá, 1970; Gray, 1971a, b; Török and Hammond, 1971; Clendenin and Szumski, 1971; Harrison and Koch, 1972; and others, some of whom are cited elsewhere in this chapter).

Following the implantation of fine-wire electrodes and routine testing, a subject needs only to be given general instructions. He is asked to make contractions of the muscle under study while listening to and seeing the MUAPs on the monitors (Fig. 6.1). A period of up to 15 minutes is sufficient to familiarize him with the response of the apparatus to a range of movements and postures.

Subjects are invariably amazed at the responsiveness of the loudspeaker and cathode ray tube to their slightest efforts, and they accept these as a new form of "proprioception" without difficulty. It is not necessary for subjects to have any knowledge of EMG. After getting a general explanation they need only to concentrate their attention. With encouragement and guidance, even the most naive subject is soon able to maintain various levels of activity in a muscle on the sensory basis provided by the monitors. Indeed, most of the procedures he carries out involve such gentle contractions that his only awareness of them is through the apparatus. Following a period of orientation, the subject can be put through a series of tests for many hours.

Several basic tests are employed. Since people show a considerable difference in their responses, adoption of a set routine earlier proved to be impossible. In general, however, they were required to perform a series of tasks. The first is to isolate and maintain the regular firing of a single motor unit (SMU) from among those a person can recruit and display with the technique described. When he has learned to suppress all the neighboring motor units completely, he is asked to put the unit under control through a series of tricks, including speeding up its rate of firing, slowing it down, and turning it "off" and "on" in various set patterns and in response to commands. More elaborate techniques now used are really only controlled versions of the original methods (Basmajian and Samson, 1973). Johnson (1976) has tested and fashioned methods that meet statistical requirements more adequately.

After acquiring good control of the first motor unit, a subject is asked to isolate a second with which he then learns the same tricks, then a

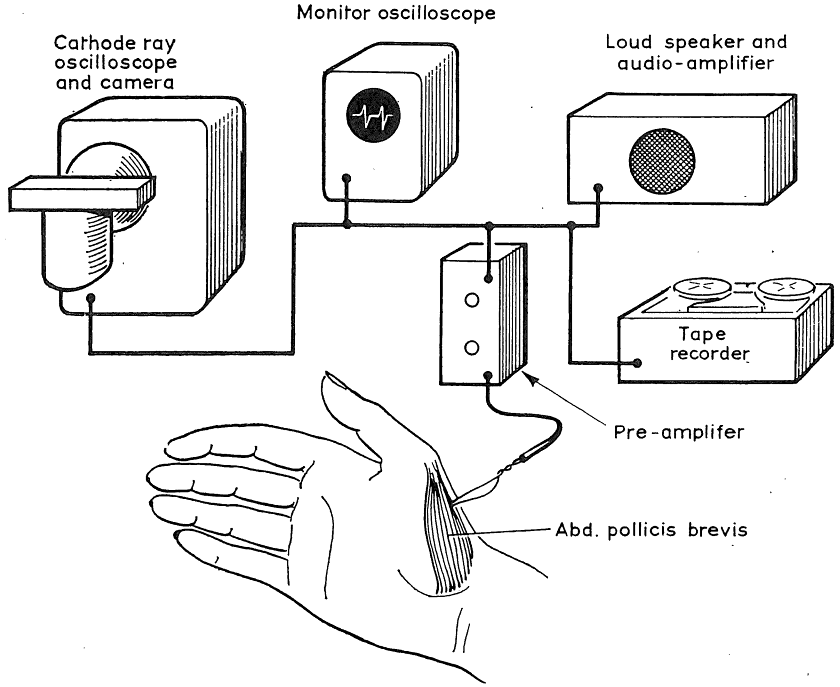

Figure 6.1. Diagram of arrangement of monitors and recording apparatus for motor unit training. (From J.V. Basmajian, ©1963, *New Scientist.*)

third, and so on. His next task is to recruit, unerringly and in isolation, the several units over which he has gained the best control.

Many subjects then can be tested at greater length on any special skills revealed in the earlier part of their testing (for example, either an especially fine control of, or an ability to play tricks with, an SMU). Finally, the best performers can be tested on their ability to maintain the activity of specific MUAPs in the absence of either one or both of the visual and auditory feedbacks, that is the monitors are turned off and the subject must try to maintain or recall a well-learned unit without the artificial "proprioception" provided earlier.

Lloyd and Leibrecht (1971) and Samson (1971) independently showed that the SMU training fulfills the requirements of the learning paradigm. The feedback methodology is not critical; thus, a highly artificial indication of successful training is satisfactory to a considerable degree. Leibrecht et al (1973) went on to show that direct EMG feedback substantially improved initial learning. The nature and amount of learning, including the ability to use proprioceptive cues in controlling an SMU, were not affected; neither was the retention of learning.

Ladd et al (1972) investigated the learning process involved in the fine neuromotor control of SMU training which, of course, also embodies inhibition of motor activity. They employed trained units in five different muscles in 25 subjects. Voluntary inhibition, they found, is a conceptual type of response showing independence of the motor component; it generalizes and transfers positively from one muscle to another. However, the voluntary contractions of an individual unit is a specific perceptual motor type of response; the motor component of the response is essential, and the learned response does not generalize or transfer from one muscle to another. Middaugh (1976) reported that subjects are not relying on peripheral factors in learning, i.e., only limited learning of peripheral sensory information and discrimination occurs. The finding by Vogt (1975) that there is little correlation between self-estimation of success and gross EMG levels of contraction in the forearm supports Middaugh's finding for motor units.

Any skeletal muscle may be selected. The ones most often reported are the abductor pollicis brevis, tibialis anterior, biceps brachii, and the extensors of the forearm. However, it is quite easy to train units in buccinator (Basmajian and Newton, 1973) and in back muscles; Sussman et al (1972) have trained units in the larynx while Gray (1971a) trained them in the sphincter ani!

ABILITY TO ISOLATE MOTOR UNITS

Almost all subjects are able to produce well-isolated contractions of at least one motor unit, turning it off and on without any interference from neighboring units. Only a few people fail completely to perform this basic trick. Analysis of poor and very poor performers reveals no common characteristic that separates them from better performers.

Many people are able to isolate and master one or two units readily; some can isolate and master three units, four units, even six units or more (Fig. 6.2). This last level of control is of the highest order, for the subject must be able to give an instant response to an order to produce contractions of a specified unit without interfering activity of neighbors; he also must be able to turn the unit "off" and "on" at will. The ultimate ability of human subjects was demonstrated by Kato and Tanji (1972a), who found that within 30 minutes their subjects could voluntarily isolate 73% of 286 motor units appearing on the oscilloscope during voluntary contractions.

CONTROL OF FIRING RATES AND SPECIAL RHYTHMS

Once a person has gained control of a spinal motor neuron, it is possible for him to learn to vary its rate of firing. This rate can be deliberately changed in immediate response to a command. The lowest limit of the range of frequencies is zero, i.e., one can start from neuromuscular silence and then give single isolated contractions at regular rates as low as 1/s and at increasingly faster rates. When the more able subjects are asked to produce special repetitive rhythms and imitations of drum beats, almost all are successful (some strikingly so) in producing subtle shades and coloring of internal rhythms. When tape-recorded and replayed, these rhythms provide striking proof of the fineness of the control.

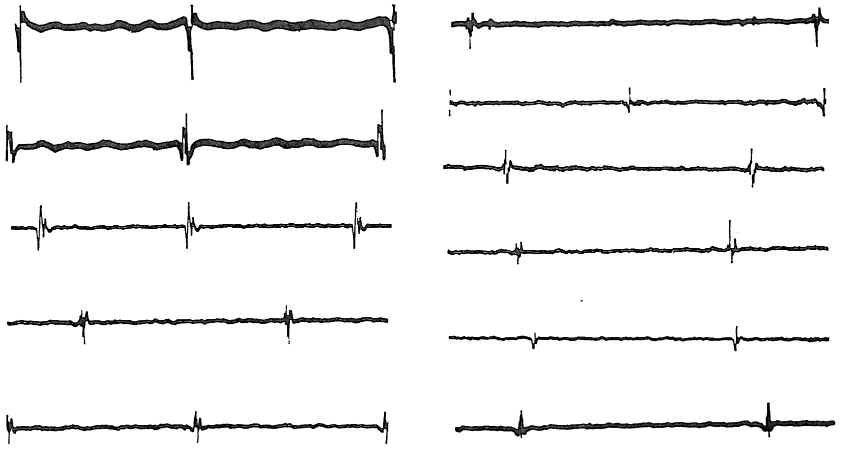

Figure 6.2. Eleven different motor units isolated by a subject in quick succession in his abductor pollicis brevis. (From J.V. Basmajian et al, ©1965, *Journal of New Drugs.*)

RELIANCE ON VISUAL OR AURAL FEEDBACK

Some persons can be trained to gain control of isolated motor units to a level where, with both visual and aural cues shut off, they can recall any one of three favorite units on command and, in any sequence. They can keep such units firing without any conscious awareness other than the assurance (after the fact) that they have succeeded. In spite of considerable introspection, they cannot explain their success except to state they "thought about" a motor unit as they had seen and heard it previously. This type of training probably underlies ordinary motor skills.

VARIABLES WHICH MIGHT AFFECT PERFORMANCE

Tanji and Kato (1971) found that cortical motor potential related to the discharge of an SMU is about the same size as that related to the contraction of whole muscles (e.g., as in key pressing). This led to their obvious conclusion that cerebral mechanisms are involved in an important manner in conscious isolation of individual motor units; they later consolidated these views with more specific tests (Kato and Tanji, 1972b; Tanji and Kato, 1973a,b). However, McLeod and Thysell (1973) did not agree; their studies of evoked EEG potentials revealed no true response in the sensorimotor areas that can be related to single motor unit activity. Intensive research is needed to resolve the question.

No personal characteristics that reveal reasons for the quality of performance have been found (Basmajian et al, 1965). The best performers occur at different ages, among both sexes, and among both the manually skilled and unskilled, the educated and uneducated, and the bright and the dull personalities. Some "nervous" persons do not perform well—but neither do some very calm persons.

Carlsöö and Edfeldt (1963) concluded that: "Proprioception can be assisted greatly by exeroceptive auxiliary stimuli in achieving motor precision." Nevertheless, Wagman et al (1965), using both Basmajian's technique and a technique of recording devised by Pierce and Wagman (1964), emphasize the role of proprioception. They stress their finding that subjects believe that certain positions of a joint must be either held or imagined for success in activating desired motor units in isolation.

Investigations of the various factors which affect motor unit training and control have added interesting features (Simard and Basmajian, 1967; Basmajian and Simard, 1967; Simard, Basmajian and Janda, 1968). They revealed that moving a neighboring joint while a motor unit is firing is a distracting influence but most subjects can keep right on doing it in spite of the distraction. This tends to agree with Wagman and his colleagues who believe that subjects require SMU training before they can fire isolated specific motor units with the limb or joints in varying positions. Their subjects reported that "activation depended on recall of

the original position and contraction effort necessary for activation." This apparently is a form of proprioceptive memory and almost certainly is integrated in the spinal cord.

Observations based on trained units in the tibialis anterior of 32 young adults showed that SMU activity under conscious control can be easily maintained despite the distraction produced by voluntary movements elsewhere in the body—head and neck, upper limbs and contralateral limb (Simard and Basmajian, 1967). The control of isolation and the control of the easiest and fastest frequencies of discharge of a single motor unit were not affected by those movements (Fig. 6.3).

Turning to the effect of movements of the same limb, Basmajian's group found that in some persons a motor unit can be trained to remain active in isolation at different positions of a "proximal" (i.e., hip or knee), "crossed" (ankle), and "distal" joint of a limb (Fig. 6.4). This is a step beyond Wagman et al (1965), who observed that a small change in position brings different motor units into action. Consequently they noted the important influence of the sense of position on the motor response. Later investigations by Simard and Basmajian showed that in order to maintain or recall a motor unit at different positions, the subject

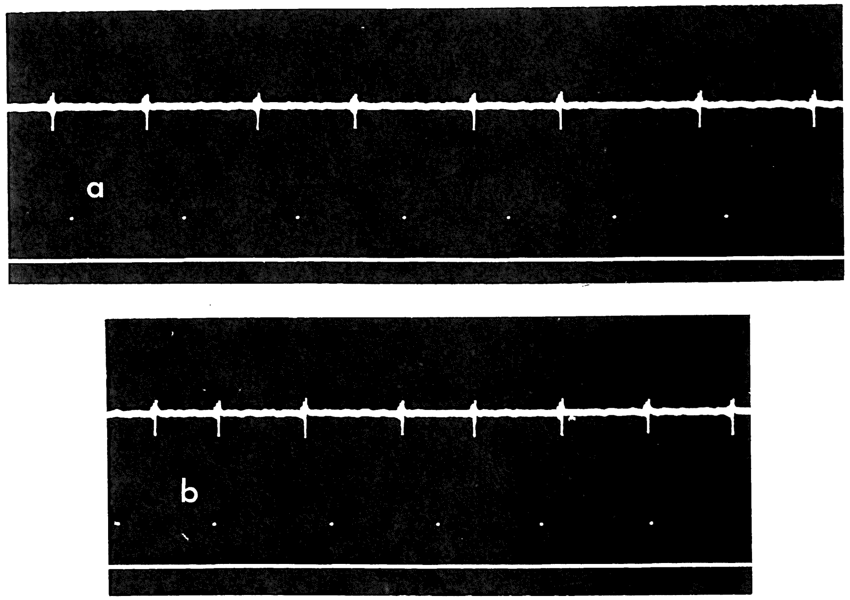

Figure 6.3. Samples of (*a*) the easiest and (*b*) the fastest rate of discharge of a motor unit in the right tibialis anterior during movements of the contralateral limb (time mark: 10 ms intervals). (From J.V. Basmajian and T.G. Simard, ©1967, *American Journal of Physical Medicine*.)

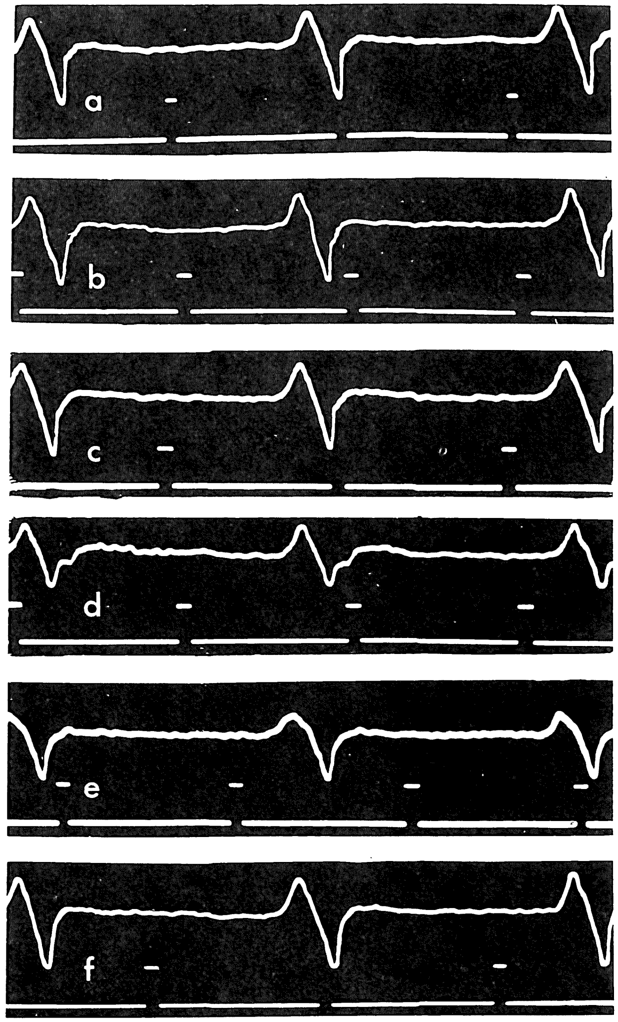

Figure 6.4. Controlled MUAP at different "held" positions of the right lower limb: *a*, neutral; *b*, in lateral rotation at the hip; *c*, in medial rotation at the hip; *d*, dorsiflexion of the ankle; *e*, plantarflexion; *f*, toes extended. (Calibration: 100 μV, 100 ms intervals.) (From J.V. Basmajian and T.G. Simard, ©1967, *American Journal of Physical Medicine.*)

must keep the motor unit active during the performance of the movements and, therefore, preliminary training is undeniably necessary.

The control of the maintenance of activity during "proximal," "crossed," and "distal" joint movements in the same limb has been proved here to be possible, provided that the technique of assistance offered by the trainer is adequate. The control over the discharge of a motor unit during proximal and distal joint movements requires a great concentration on the motor activity. But when one considers the same control during a "crossed" joint movement, there are even greater difficulties for obvious reasons.

The observation that trained motor units can be activated at different positions of a joint is related to the work of Boyd and Roberts (1953). They suggested that there are slowly adaptive end organs of proprioception which are active during movements of a limb. They observed that the common sustained discharge of the end organs in movements lasted for several seconds after attainment of a new position. This might explain why a trained single motor unit's activity can be maintained during movements.

Lloyd and Shurley (1976) studied the hypodynamic effects of sensory isolation on single motor units recorded through wire electrodes in 40 normal subjects. A light panel indicated the trial onset, correct, and incorrect response. Isolation condition was produced by an air-fluidized, ceramic-bead bed in a light and sound attenuating chamber. A relearning session followed the initial session after a 2-week interim rest. Subjects were randomly assigned to the isolation or nonisolation condition for both sessions. The hypodynamic effects of sensory isolation increased the speed of learning to isolate and control an SMU. The results suggested that subjects were better able to attend to the relatively weak proprioceptive information provided by the SMU through the reduction of the amount and/or variety of competing stimuli.

The Level of Activity of Synergistic Muscles

The problem of what happens to the synergistic muscles at the "hold" position or during movements of a limb has been taken into consideration only in a preliminary way. The level of activity appears to be individualistic. Active inhibition of synergists is learned only after training of the motor unit in the prime mover is well established. Basmajian and Simard (1967) clearly demonstrated that as the subject focuses his attention on feedback from an SMU in one muscle (tibialis anterior), the surrounding muscles become progressively relaxed to the point of complete silence when isolation of the SMU is complete. Only such motor units in a limb as are needed to maintain its particular posture are still active. The process of "active inhibition," probably the more dramatic element of motor unit training, is thus achieved.

Influence of Manual Skills

Although the earlier studies failed to reveal any correlation between the abilities of subjects to isolate individual motor units and the variable of athletic or musical ability, a systematic study by Scully and Basmajian (1969) cast some light on the matter. They used the base time required to train motor units in one of the hand muscles as the criterion. Surprisingly, the time required to train most of the manually skilled subjects was *above* the median.

Henderson's (1952) work offers an explanation: the constant repetition of a specific motor skill increases the probability of its correct recurrence by the learning and consolidation of an optimal anticipatory tension. Perhaps this depends on an increase in the background activity of the γ-motoneurons regulating the sensitivity of the muscle spindles used in performing the skill. Wilkins (1964) postulated that the acquisition of a new motor skill leads to the learning of a certain "position memory" for it. If anticipatory tensions and position memory, or both, are learned, spinal mechanisms may be acting temporarily to block the initial learning of a new skill. Perhaps some neuromuscular pathways acquire a habit of responding in certain ways and then that habit must be broken so that a new skill may be learned. The "unstructured" nature of learning a motor unit skill would make this mechanism even more likely (Basmajian, 1972).

Influence of Age and Gender

Although the training of fine control of individual units is complicated when children are involved, it is possible in children even below the age of 6 years (Fruhling et al, 1969). Simard and Ladd (1969) and Simard (1969) have further documented the factors involved.

Zappalá (1970) found only minor gender differences in the ability to isolate SMUs; males showed some superiority. In a different type of experiment, Harrison and Koch (1972) and Petajan and Jarcho (1975) found the opposite, but again the differences were not impressive.

Influence of Competing Electrical Stimulation

Any changes in the action potentials of trained motor units as a result of electrical stimulation of the motor nerve supplying the whole muscle must reflect neurophysiologic changes of the single neuron supplying the motor unit. Therefore, Scully and Basmajian (1969) investigated the influence of causing strong contractions in a muscle to compete with a discrete SMU in it which was being driven consciously. Each of a series of subjects sat with his forearm resting comfortably on a table top. The stimulator cathode was applied to the region of the ulnar nerve above the elbow. The effective stimuli were 0.1-ms square-wave pulses of 70 to 100 V, delivered at a frequency of 90 pulses/min. Because stimuli of this order are not maximal, all axons in the ulnar nerve were not shocked, and slight variation must have existed in axons actually stimulated by each successive shock.

Contrary to expectation, when the massive contraction of a muscle was superimposed on the contraction of only one of its motor units, the regular conscious firing of that SMU was not significantly changed. These experiments leave little if any doubt that well-trained motor units are not blocked in most persons. Even the coinciding of the MUAP with elements of the electrically induced massive contraction would not abolish the SMU potential.

Influence of Cold

Brief cutaneous applications of ice over the biceps brachii in which an isolated motor unit had been trained elicited facilitation of both background activity and spontaneous activation of the trained SMUs (Clendenin and Szumski, 1971). Wolf, Letbetter and Basmajian (1976) confirmed this finding, using a special electronic cooling device (Wolf and Basmajian, 1973). Seventeen subjects discharging SMUs at a comfortable resting rate (5.2 ± 0.9 pps) tended to get an inhibitory response in the initial minute of cooling. Most subjects (13 of 18) who held SMU discharges to 0.5 pps first got an increase, and then a significant decrease. Apparently the central excitatory state is the mediator of these local motor reactions to cutaneous cooling.

Effects of Handedness and Retesting

When a large number of subjects were studied on two occasions using a different hand each time, Powers (1969) found that they always isolated a unit more quickly in the second hand. Isolation was twice as rapid when the second hand was the preferred (dominant) hand; it was almost five times as rapid when the second hand was the nonpreferred one. The time required to control a previously isolated unit was shortened significantly only when the preferred hand was the second hand. However, in a test-retest situation with much fewer subjects, Harrison and Koch (1972) found no significant improvement from test to retest.

Influence of Disease States

While Basmajian has found that partially paralyzed people can learn SMU controls quite easily, the factor of spasticity introduces considerable difficulty. In clinical studies, one can overcome these difficulties by carefully training the patient to relax spastic muscles. Parkinsonian rigidity seems to be a different matter. Petajan and Jarcho (1975) reported that patients with Parkinson's disease are unable to adjust the firing rate of motor units that initiate contraction from zero to higher rates. Although the frequency modulation is not normal, motor units recruit in an orderly fashion. Levodopa treatment restores normal control of SMUs.

REACTION TIME STUDIES

A number of investigators have used trained SMUs for psychological testing of reaction time (RT). Thus, Sutton and Kimm (1969, 1970) and Kimm and Sutton (1973) have shown stable differences in the RT in triceps and biceps brachii and a slowing of RT following the intake of alcohol. Generally, they concluded that SMU spike RTs were slower than that obtained from the gross EMG signals and lever-press RTs. But Thysell (1969) disagrees, finding them to be comparable and rather like those of Luschei et al (1967). Furthermore, Vanderstoep (1971) questions the finding of inherent differences between muscles when the RT paradigm is used with triceps, biceps, the first dorsal interosseus, and the abductor pollicis brevis. Zernicke and Waterland (1972), on the other hand, were able to show differences between the two heads of biceps brachii. The short head contains motor units that are easier to control than those in the long head. They related this to various morphological and functional requirements of the two heads (e.g., the density of muscle spindles is greater in the short head). The willful fractionization of control between two heads of the same muscle, not entirely unexpected in view of the fineness of willful controls involved in SMU control, once more underlines the discrete nature of controls over the spinal motoneurons.

PRACTICAL APPLICATIONS

Many applications are emerging for the use of motor unit training, e.g., in the control of myoelectric prostheses and orthoses, in neurological studies, and in psychology. The growth of the field of "biofeedback" from this work is the subject of a separate book (Basmajian, 1983). Therefore, only a brief outline is given in the remainder of this chapter as it applies to myoelectric biofeedback only, employing the EMG of a much grosser nature than SMU potentials—although the feedback principles controlling them are common to both.

EMG BIOFEEDBACK

Relaxation. Following confirmation of early studies of the single motor unit principles, Green et al (1969, 1970) rapidly extended biofeedback work into the clinical investigation of the effects of feedback relaxation. They combined this with other forms of electronic feedback and applied the results to a variety of general and local tension states believed to be the cause of pathological physiology. Simultaneously, Gaarder (1971) was exploring practical means to control relaxation in patients with feedback devices.

Hoping to determine whether an ability to produce EMG patterns accurately reflects the ability to achieve specific muscle tensions, Rummel (1974) studied a long series of normal subjects. She was amazed to find no statistically significant correlation. Schwartz et al (1976a, b), on the other hand, revealed patterns of covert activity in facial muscles that could be graded and correlated to states of affective imagery and mood. Earlier, Smith (1973) had found a positive correlation between personality traits of anxiety and EMG activity from the region of the forehead. This finding disagreed with the earlier work of Iris Balshan Goldstein (1962), but it must be remembered that Smith's forehead electrodes often pick up from a wide area (down to the clavicles). Similar findings were reported for the muscles of the jaw by Thomas et al (1973) in explaining temporomandibular joint syndrome. Chapman (1974) showed that EMG activity from the forehead reflected even the fact that the subjects were not alone but were in an audience (i.e., in a social facilitation setting). Biofeedback appears to be superior to verbal feedback in inducing relaxation, at least in the research models used by Kinsman et al (1975) and Coursey (1975), but Alexander (1975) disagreed on the basis of his research.

PSYCHOPHYSIOLOGICAL MECHANISMS

The question continues to arise: Is biofeedback training based on volition or is it operant conditioning? Hefferline and Perera (1963), in their continuing search for the effect of proprioception in behavior, showed that subjects could be conditioned to respond to covert twitches in a thumb muscle (displayed by EMG). After the EMG feedback was eliminated, the response often persisted. By coincidence the muscle used (abductor pollicis brevis) was the same as the one used in the early experiments on SMU training (Basmajian, 1963). Instead of asking the subject to shape the behavior of the EMG signal within the target muscle, Hefferline and Perera conditioned him to press a key using another muscle. Their system was based on the operant conditioning paradigm. Fetz and Finocchio (1971) were able to condition awake monkeys to give bursts of cortical cell activity with and without simultaneous suppression of EMG activity in specifically targeted arm muscles. Operant conditioning methodologies proved sufficient to bring about the correlated response.

In man, Germana (1969) demonstrated quite adequately and not surprisingly that conditioning may be employed in modifying EMG responses; perhaps more importantly, his work has tended to support "cardiac-somatic coupling," with which Obrist and various colleagues have been concerned (see Obrist, 1968). Cohen and Johnson (1971) found a high correlation between heart rate and muscular activity, supporting Obrist's theoretical position. Subtle changes in muscular activity did change heart rate both when subjects were intentionally modifying muscular activity as well as when spontaneous changes were occurring.

Refining his techniques, Cohen (1973) soon after showed a relationship only in subject groups that had a moderately high EMG output from skin electrodes over the muscles of the chin; lower EMG outputs seemed unrelated to heart rate changes; thus the "cardiac-somatic coupling" is not absolute, and mechanisms must exist in the central nervous system for separating cardiac and peripheral motor responses. Other autonomic functions have been linked with covert motor responses; thus, Simpson and Climan (1971) have shown that there is some apparent effect of muscular activity on the pupil size during an "imagery" task in which subjects generated images in response to words.

GENERAL RELAXATION (CONTINUED)

In the 1920s and 1930s, Edmund Jacobson of Chicago became the enthusiastic proponent of a clinical form of EMG monitoring of his patients' progress during relaxation training. Limited by the apparatus available at the time, Jacobson developed methods of electrical measurement of the muscular state of tension and employed his measurements to induce progressive somatic relaxation for a variety of psychoneurotic syndromes (Jacobson, 1929, 1933). Green et al (1969) and Gaarder (1971), using a modification of the SMU training technique, found that EMG biofeedback training would be useful in many states. Mathews and Gelder (1969) studied the effect of relaxation training with phobic patients, showing that the EMG (among other parameters) was altered during relaxation and concluding that relaxation is in some way associated with a controlled decrease in "arousal level" with retention of consciousness. Paul (1969) compared hypnotic suggestion and brief relaxation training, showing the superiority of the latter in reducing subjective tension and distress. Wilson and Wilson (1970), while agreeing that muscle tension could be manipulated by feedback and conditioning, were much less sure of the desirable effects of relaxation. Dixon and Dickel (1967), Jacobs and Felton (1969), Whatmore and Kohli (1968), and Budzynski and Stoyva (1969) also contributed to the literature of EMG biofeedback in relation to general clinical disorders, especially tension headache.

Chronic anxiety is often reflected in overactivity in the general body musculature. Townsend et al (1975) compared treatment of chronic anxiety with EMG biofeedback to treatment with group therapy in a control group. Significant improvements resulted, as they did in a study by Canter et al (1975) in which they compared biofeedback with Jacobsonian progressive relaxation. While the latter was effective, the biofeedback approach proved superior in reducing both muscular tension and chronic anxiety.

Dental specialists are increasingly enthusiastic about the new treatment of the common and distressingly painful jaw pain (temporomandibular joint syndrome) caused by over-active use of muscles that are normally relaxed or only lightly contracted. Myoelectric biofeedback training involves making the patient aware of hyperactivity in the masseter muscle and then training local relaxation of the muscle (Carlsson et al, 1975).

Speech Apparatus and EMG Feedback

As noted in the earlier editions of this book, Hardyck et al (1966) were among the first to modify the lessons of SMU training to applied biofeedback of useful function. Using feedback from surface EMG of the laryngeal muscles during silent reading, they were able to accelerate the reading skills of slow readers. Simultaneously McGuigan and various associates at Hollins College, Virginia were studying the covert oral language behavior as measured by surface EMG of chin muscles (McGuigan, 1966, 1970; McGuigan and Rodier, 1968). Inouye and Shimizu (1970) examined the hypothesis that verbal hallucination is an expression of so-called "inner speech."

The Czech investigators Baštecký et al (1968a, b), using delayed auditory speech feedback and EMG of mimic muscles (primarily mentalis at the chin), found that schizophrenic patients could be differentiated from normal subjects. This area of research, now in its infancy, requires a great deal of investigation. Thus, Sussman et al (1972) have shown that individual units in the laryngeal muscles can be trained. The same group (Hanson et al, 1971; MacNeilage et al, 1972; MacNeilage and Szabó, 1972; and MacNeilage, 1973) have systematically exposed mechanisms of fine control of the laryngeal function which should have far reaching use.

Stuttering has been the special concern of Barry Guitar (1975). He taught stutterers to reduce resting EMG activity in the lips and in the laynx. With myoelectric biofeedback through fine-wire electrodes in the lips and buccinator muscles of the cheek, clarinet players can quickly revise the localized activities in bizarre ways without losing the ability to perform (Basmajian and Newton, 1973). Also trumpet and trombone players have different natural patterns that vary with proficiency and that can be altered with EMG feedback (Basmajian and White, 1973; White and Basmajian, 1973).

TARGETED MUSCLE RETRAINING AND REHABILITATION

Ladd and Simard (1972), building on earlier work on SMU training, trained and studied congenitally malformed children with the aim of using the limited sources of muscle power for myoelectric and other types of artificial limbs and orthoses. Payton and Kelley (1972) explored the factors controlling biceps brachii and deltoid during performance of skilled tasks in a way that lends itself to feedback training.

Practical approaches with practical biofeedback instruments became a reality with commercial equipment being marketed. Booker et al (1969) demonstrated retraining methods for patients with various neuromuscular conditions, and Johnson and Garton (1973) succeeded with hemiplegic patients in retraining functions of the upper and lower limbs where other methods proved inadequate. What has been surprising to many people is the ease with which ordinary patients "take to" the feedback signals and learn to manipulate them by acquiring more precise control over the muscles requiring training or recruitment.

This book is not the place for details of how EMG biofeedback may be used in rehabilitation. The topic has been covered thoroughly in *Biofeedback: Principles and Practice for Clinicians, 2nd Edition, 1983.*

RELATED PSYCHOLOGICAL RESEARCH

Since the valuable start given to it by the Montreal group in the early 1950s (see Malmo et al, 1951; Malmo and Smith, 1955), a sort of electromyographic subculture has existed in the psychological literature.

Following up a previous investigation of limb positioning with kinesthetic cues (Lloyd and Caldwell, 1965), Lloyd (1968) found no statistically significant relationship between position accuracy and the amount of contralateral activity as measured by EMG techniques, but there was no doubt that such activity exists at a low level, especially during passive movement of the ipsilateral limb. Lloyd concluded that a minimal level of activity was required for kinesthetic mediation of accurate limb position. It was this work that led Lloyd and his colleagues to study SMU responses (cited earlier in this chapter).

Wiesendanger et al (1969) measured simple and complex reaction times with the EMG signal of biceps and triceps. While their chief concern was to find differences between normal persons and patients with parkinsonism—there were none in the simple tasks—they showed that the normal reciprocal inhibition of antagonists was modified in different ways, with biceps activity always being present (see the general discussion of agonist-antagonist behavior). Bartoshuk and Kaswick (1966) had shown earlier that general arousal level may not be necessary to produce EMG gradients; instead, selective facilitation may be sufficient.

The influence of environmental and emotional factors on EMG activity is gaining widespread interest. A good example of this type of study is that of Lúkas et al (1970), who recorded the effect of sonic booms and noise from subsonic jet flyovers on skeletal muscle tension (in the trapezius muscle) as well as other parameters. The EMG activity increased with sonic booms with lesser effect from the flyover noise.

Phasic changes in muscular and reflex activity during non-REM sleep were demonstrated in man and cats by Pivik and Dement (1970). The suppression of EMG activity from surface electrodes in the submental (chin) area was observed in all subjects during non-REM sleep but occurred with the greatest frequency during sleep stages 2 and 4. The suppressions averaged ¼ minute in duration and exhibited a higher frequency in the 10 minutes prior to the REM period than after. Larson and Foulkes (1969) confirmed that EMG suppression in chin and neck muscles heralds REM sleep onset. The amount of EMG activity during non-REM sleep just prior to being awakened influences the recall frequency of dreams.

Pishkin and Shurley (1968) and Pishkin et al (1968) demonstrated a positive correlation between EMG responses and concept-identification performance which produces cognitive stress. About the same time, Aarons (1968) was exploring possible diurnal variations of myopotentials and word associations related to psychological orientation. Word-association tests revealed qualitative differences among responses before sleep, upon awaking, and at noon. Some differences were related to psychological test variables (kinesthetic orientation, "need for change," and anxiety); the other influences were the time of the tests and, apparently, the intensity of EMG response. EMG levels during sleep correlated highly with electroencephalographic sleep stages.

This brings us back to a group of studies on the effects of stress and anxiety on the EMG, first adequately investigated by Goldstein (1962). Brandt and Fenz (1969) showed a peak of forehead EMG activity in conditions of induced mild stress, suggesting it might reflect inhibitory control. Incidentally, they questioned the specificity of the forehead source as the ideal one for such experiments—and well they might, for with intramuscular wire electrodes the frontalis and corrugator supercilii are silent unless the face shows clear emotive responses (Vitti and Basmajian, 1973). Fridlund et al (1980, 1982) concluded that the general tension factor reflects agitation more than elevated tonic muscle activity.

Searching for a suitable muscle for stress-EMG studies, Yemm (1969a, b) of Bristol, England, concentrated on the masseter—not surprisingly, for he is a dental scientist. He found an increase in masseter EMG activity during the stress of cognitive manual task performances in this postural muscle of the jaw. With patients who have temporomandibular dysfunction, the EMG responses persisted abnormally long (Yemm, 1969c).

The use of muscles active in maintaining human posture has other advocates. Thus, Avni and Chaco (1972) used the EMG activity of supraspinatus muscle (which is described elsewhere in this book in its shoulder-posture role). Reasoning from earlier work (Basmajian, 1961; Basmajian and Bazant, 1969) that drooping of the shoulder should influence supraspinatus activity, they studied a series of depressed patients. While normal controls showed normal antigravity reflex activity, depressed patients all showed significant decrease while they were depressed but recovered the normal pattern on recovery from depression.

NOTES ON TECHNIQUE

The use by Avni and Chaco and by Yemm of postural muscles (noted above) rather than surface EMG of chin and forehead raises the general question of appropriate methods for EMG studies of tension. Unquestionably, some of the techniques employed by investigators naive in electromyography have been less than acceptable. Most EMG activity from the submental region would appear to reflect the frequency of swallowing—which, of course, may be a good criterion of tension. (For swallowing EMGs, see Chapter 19.) As noted before, forehead EMG work also may be questionable, although obvious facial mimicry often represents inner states and so, in a distressed person, may be a satisfactory source of EMG signals.

In the hands of experts good surface EMG is quite adequate for tension studies. Bruno et al (1970) and Kahn (1971) have even demonstrated its usefulness for precise identification of signals. But the factors affecting the reliability of surface EMG signals are many and appear to be ignored by many psychologists; they ought to read and reread the paper by Grossman and Weiner (1966) as well as the details in Chapter 2 in this book.

The foregoing facts mean that to be useful in biofeedback practice, integrated rectified EMG signals from the forehead or frontal region need not come from frontalis muscle. Indeed, a wide source of myopotentials is much to be preferred as a reflection of general nervous tension. But we should admit that (1) wide-source myopotentials are not "frontalis EMG" and (2) the numbers of "microvolts" produced on the meter of a commercial device or any other device simply indicate a microvolt reading at the input of the device. The integrated rectified EMG signal from forehead surface electrodes generally reflects the total or global EMG of all sorts of repeated dynamic muscular activities down to about the first rib—along with some postural activity and nervous tension overactivity. The exact meter readouts can be taken with a grain of salt by the knowledgeable electromyographer at the same time that he is deliberately and wisely using them as (1) a rough indicator of progress in a clinical relaxation training program and (2) a visual placebo in reinforcing the patients' responses. Any higher level of reliance on such inflated numbers is self-deception (Basmajian, 1976).

CHAPTER 7

EMG Signal Amplitude and Force

The surface EMG signal may be conveniently detected with minimal insult to the subject. For this reason it has become very useful in many applications which require an assessment of the muscular effort. The reader is referred to the material in Chapter 2, which addresses the details of this issue.

A considerable controversy exists concerning the description of this relationship. Early theoretical studies (Person and Libkind, 1967; Bernshtein, 1967; Moore, 1967; Libkind, 1968 and 1969) all suggested that, for isometric contractions, the amplitude of the EMG signal should increase as the square root of force generated by the muscle when the motor units are activated independently. These studies were instrumental in generating interest in providing a more structured approach to the interpretation of the EMG signal-force relationship. It is now clear that the assumptions and approximations which were made were simply too generous. The reader is referred to the relationships and associations between the EMG signal, as a function of force and time, with known physiological correlates displayed in Figure 3.9. In those expressions it is apparent that the relationship is complex. In fact, surprisingly few experimental results support the square root relationship. Almost without exception, investigators report either linear relationships or a more than linear increase of the EMG signal with increasing force.

RELATIONSHIP DURING ISOMETRIC CONTRACTIONS

Monotonically Increasing Contractions

Table 7.1 provides a sample of the studies relating to this issue which have been reported in the literature between 1952 and 1979. No attempt has been made to include all the published reports. The contents of the table were designed to represent the wide variety in and disparity among the wealth of studies which have been performed. These investigations are characterized by considerable variability in the muscles examined, the types of contractions performed, and the quantities derived from the raw data to represent the amplitude of the EMG signal.

Beyond the obvious disparities among the reported studies, it is necessary to consider particulars which are specific to the muscle or muscle group which is involved in the force generation process. For example, (*a*) Relatively small muscles, such as those in the hand, and relatively large muscles in the limbs are controlled by different firing rate-recruitment schemes. For additional details on this point, the reader is referred