

Electrical Stimulation: Neurophysiological Basis and Application

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Abstract

Electrical stimulation has been used for thousands of years for a variety of purposes including muscle reeducation, muscle strength training and wound healing. However, because it has been used most commonly by individuals in money making schemes, it has been sometimes considered the domain of quacks and charlatans. But electrical stimulation can be a potent tool in the clinical setting if properly used for muscle strength training, endurance training, reducing muscle spasticity, motor reeducation and even wound healing. The present paper describes the history of electrical stimulation and the most common therapeutic uses and delves in to the pros, cons and precautions of using this therapeutic modality.

Key words: paralysis, paraplegia, diabetes, electrical stimulation, stroke.

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In 1744 a German scientist whose name was Krueger wrote “*but what is the usefulness of electricity, for all things must have a usefulness that is certain. Since electricity must have a usefulness and we have seen it cannot be looked for either in theology or in juris prudence there is nothing left but medicine. The best effect would be found in paralyzed limbs to restore sensation and reestablish the power of motion*” [56]. In this early treatise, Krueger felt that there must be a practical use in medicine for electrical stimulation but could not readily find it. Over the years, however, electrical stimulation has evolved as a technique to retrain partially paralyzed muscles after stroke [57], to regain strength after surgical procedures to the knee [37], and, in general conditioning after cardiac surgery [58]. It has been used quite frequently for such modalities as healing difficult bone fractures [7] and has been used for patients with stroke or spinal cord injury to reduce muscle spasticity [17, 59, 68, 70]. Electrical stimulation has been shown to increase the circulation to skin and muscle [40, 62]. In general, electrical stimulation has been used (1) to increase strength and endurance of muscle, (2) improve range of motion, (3) neuromuscular reeducation [12], (4) pain management, (5) reducing edema [33], and (6) as an aid in the healing of bone fractures and pressure sores. This paper will review the use of electrical stimulation for some of these modalities and review its use and contraindications.

The use of electrical stimulation for restoring strength and endurance

In this arena, electrical stimulation has been used to increase strength and endurance in partially and fully paralyzed muscle. It has been used for peroneal nerve stimulation [10, 69], the restoration of shoulder movement [21], recovery of tendonesis grip [22], and in the use of an upper arm prosthesis [39].

Spot training of muscle

In general, the principle behind using electrical stimulation for fully paralyzed, partially paralyzed, or muscle injured due to surgical intervention is that electrical stimulation becomes the substitute for normal volitional control. This is particularly important when training individual heads of complex muscles. For example, the quadriceps muscle has 4 heads. If one head is injured due to a sports injury, electrical stimulation can spot train one of the 4 heads while leaving the other heads alone. This allows balancing of the muscle so that the one head is strengthened to the strength of the other heads to allow a balanced contraction to extend the knee [47]. Volitional effort does not allow spot training of individual portions of muscle groups causing the uninjured part of the group to increase in strength to substitute for the damaged part of the muscle during exercise.

Mechanism of action of electrical stimulation

Generally speaking, electrical stimulation does not directly stimulate skeletal muscle. Electrical stimulation actually excites the motor nerve going to muscle and not

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muscle itself. Therefore, high frequency stimulation (greater than 70 Hertz) will cause neuromuscular junction failure and muscle will rapidly fatigue [41, 46]. The optimum frequency is similar to the range of normal motor unit discharge frequencies generated during voluntary activity, 20-50 Hz [46, 51]. Lower frequencies cause an unfused muscle contraction [46]. One common problem is pain during stimulation.

Optimizing electrical stimulation

The motor nerve is most susceptible to stimulation at the point it branches to enter the muscle, called the motor point. Therefore, the closer the electrode is to the motor point, the less current it takes to stimulate the muscle through its nerve. Coincidentally, the motor point has the greatest density of sodium channels and therefore the lowest impedance and is the easiest point to stimulate [63]. In practice, by moving an impedance probe over the muscle, the point where the motor point enters the muscle can be easily found. This point produces less pain and the strongest muscle contraction when applying electrical stimulation [6, 16, 29, 36]. Further the lower the density of current under an electrode, the less pain will be felt and therefore, electrode size is another important consideration [16].

In general, it has been shown that larger electrode pad sizes allow for better toleration of stimulation [2, 3]. The larger the pads the lower the current density, and hence less pain. However, the larger the electrode size, the larger the muscle mass that is excited and the less specific the contraction to a single muscle or group of muscles [16]. Therefore, it is especially important to avoid unwanted contractions in neighboring muscles by using the smallest electrode size possible to give the greatest specificity but the least pain [61]. This is especially true in the pediatric population [11]. Standard electrode sizes are generally approximately 2x2 or 2x4 centimeters depending on the size of the muscle being studied. Curiously, in recent studies we have found that

the most important parameter is the placement of the electrode in maximizing muscle contraction and minimizing pain. Electrodes should be placed over the motor point. Whether electrodes are square, round or oval shaped has no effect on the ability of the electrode to elicit a strong contraction and minimize pain in muscle [16]. Therefore, while the shape of the electrodes may be a good marketing ploy by many companies, it is meaningless clinically.

Gracinin et al [19] and Milner et al [30] found that a pulse width of 250-300 microseconds elicited the minimum pain response. Moreno-Aranda and Seireg [34] suggested that instead of stimulating with a square wave, a modulated high frequency sine wave would produce the least pain. This type of stimulation, called Russian stimulation, has been shown to produce less contraction at more pain than square wave stimulation in recent studies [6]. The optimum waveform seems to be biphasic sine wave stimulation to produce the greatest strength in muscle and the least pain when comparing square to sine to Russian and Interferential stimulation [6, 16].

It is equally important to use proper electrodes. The best electrodes are carbonized rubber electrodes with a hydrogel electrolyte. Silver electrodes should never be used as they have been linked to cancer of the skin. The electrode gel must have good pH buffering to avoid electrode burns [47].

Anaerobic and Aerobic exercise

Electrical stimulation, once applied properly with the appropriate electrical stimulator, can be used for muscle strengthening [55, 53, 54] or for even restoration of movement in paralyzed individuals [49, 25].

Perhaps the easiest way to see the effect of electrical stimulation is in individuals that are fully paralyzed. Unlike voluntary effort, where individuals may receive some benefit from electrical stimulation but also can exercise on their own, individuals that are fully paralyzed can only exercise with electrical stimulation. For example, in figure 1, a subject is undergoing electrical stimulation of her abdominal and lower leg muscles. This type of exercise, most commonly involves isometric or isokinetic contractions. In contrast, electrical stimulation, sometimes called functional electrical stimulation (FES), can be used for individuals to accomplish aerobic exercise when computers are used to synchronize multiple muscle movement as shown in figure 2. Isometric exercise is commonly used to build strength while aerobic exercise is used to train the cardio-respiratory axes and build endurance. Generally, while electrical stimulation is used to elicit isometric contractions, stimulation parameters can be adjusted so that amplitude of stimulation can be increased as muscles fatigue thereby allowing for sustained muscle contractions.



Figure 1 – A subject using electrical stimulation for strength training.

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If individuals engage in voluntary isometric muscle contraction at various percents of their maximum strength (MVC), then the length of time that they can sustain that tension before they fatigue is called the endurance time. In figure 3 typical endurance times are shown in healthy male volunteers accomplishing isometric contractions of their quadriceps muscles at strengths ranging from 10 to 100% of their maximum strength. Generally, contractions at 10% or less of the maximum strength do not cause muscle fatigue and therefore the endurance time is infinitely large. As seen in this figure, sometimes called a Rohmert curve, endurance exponentially declines with increasing tension on the muscles, such that by the time contractions are sustained at tensions of about 30% MVC, endurance is less than 200 seconds whereas contractions of 100% MVC last only approximately 1 second [24, 45, 41]. When electrical stimulation is used to sustain isometric contractions to fatigue, endurance is generally less at most tensions. For example, at 20% of the maximum strength, endurance is approximately 25% less in figure 3 for individuals who are paralyzed sustaining isometric contractions of the quadriceps muscles when compared to control subjects sustaining contractions through voluntary effort. The difference is usually attributed to differences in recruitment order. The normal recruitment order for motor units during voluntary contraction is from the smallest motor units to larger motor units respectively [41, 46]. This principle, called Hennemans principle, allows small nonfatiguable

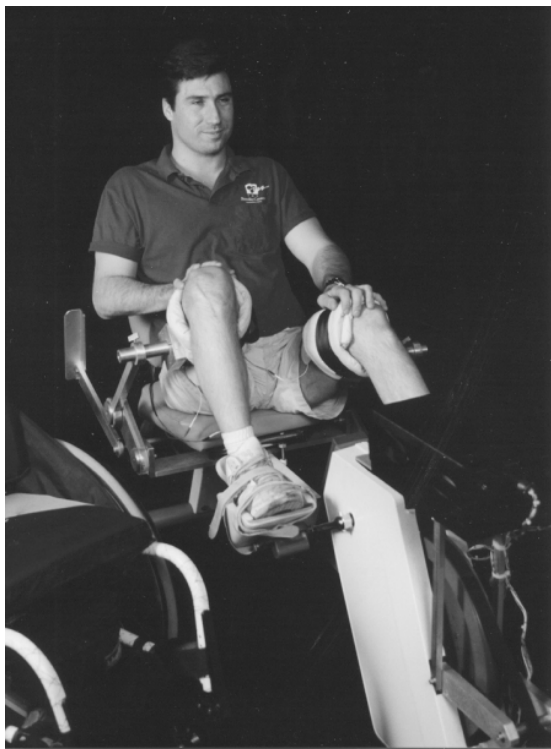


Figure 2. An individual with spinal cord injury on a bicycle using electrical stimulation.

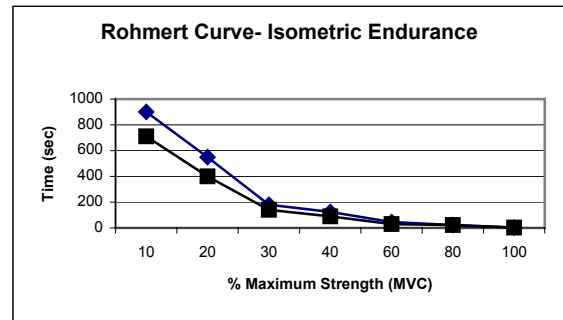


Figure 3. This figure illustrates the relationship between the endurance time for isometric exercise induced by voluntary effort (diamonds) and by electrical stimulation of paralyzed muscles (squares). Endurance time is shown for fatiguing isometric contractions at different percentages of the muscles maximum strength (MVC).

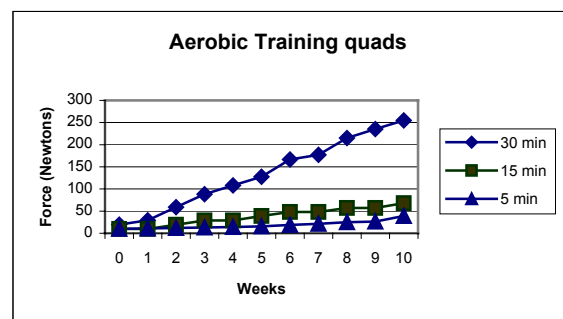


Figure 4. This figure illustrates the change in maximum muscle force in subjects that have a spinal cord injury that are fully paralyzed, when exercising on a FES bicycle ergometer. Illustrated here is the increase in muscle force over a period of 10 weeks, in a group of subjects, when training for 30 minutes 3 times per week, 15 minutes 3 times per week, and 5 minutes 3 times per week.

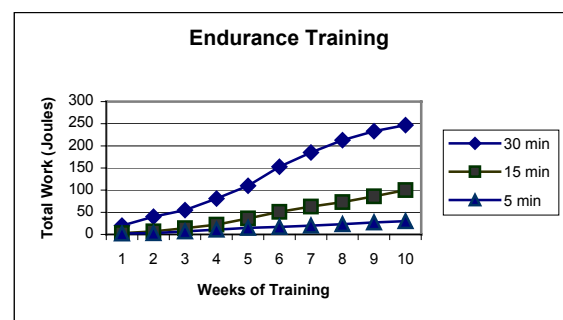


Figure 5. This figure illustrates the total aerobic work accomplished during 10 weeks of aerobic training on an FES cycle ergometer in 4 subjects with complete spinal cord injury when exercising 30 minutes per day 3 times per week, 15 minutes per day 3 times per week, and 5 minutes per day 3 times per week. The total work accomplished during a fatiguing training session is shown in joules on the y-axis.

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motor units to usually be recruited first, followed by large fast twitch non-oxidative motor units [31]. In contrast, muscles respond to electrical stimulation by recruiting the larger motor units first, that is the fast twitch glycolytic motor units versus the slow twitch oxidative motor units. This difference in recruitment order causes higher fatigability in muscle [24]. However, there is a striking similarity in the shape of the Rohmert curve for both [41].

Whereas most therapeutic uses of electrical stimulation involve isometric exercise, a great body of research involves the use of electrical stimulation for aerobic exercise [41, 47, 54]. As shown in figure 2, cycle ergometers have been developed that use electrical stimulation such that people with stroke or spinal cord injury can exercise aerobically even if they do not have the volitional control to exercise on their own. Electrodes are applied to the quadriceps, hamstring, and gluteus maximus muscles. Patients sit on the cycle ergometer, as shown in figure 2, and the computer then controls the appropriate sequencing of stimulation of the muscles such that individuals can peddle the ergometer. As shown in figure 4, when individuals exercise aerobically, both the force of the muscle (strength) and the endurance (figure 5) increase progressively with weeks of training. For example, as shown in figure 4, the strength of the muscle (shown as the force in Newtons) after 30 minutes of cycling, 3 days per week, increases continuously throughout 10 weeks of bicycling. In addition to the increase in muscle strength of the quadriceps, hamstring, and gluteus maximus muscles (figure 4 shows quadriceps muscle strength) the endurance, as shown by total work accomplished also increases on a weekly basis. There seems to be a critical threshold of minimum training necessary to increase endurance. For example, in figures 4 and 5, if exercise is only accomplished for 5 minutes 3 times per week, there is only a small increase in both muscle strength and endurance over 10 weeks of cycle ergometry. On the other hand, 15 minutes of exercise causes only a marginal difference in strength and endurance. Proper conditioning seems to take approximately 30 minutes of exercise at 3 times per week for proper aerobic training of the quadriceps muscles for strength and endurance training with bicycle ergometry. Thus the old adage that a minimum of 20 minutes a day of aerobic training is necessary is certainly true here [27].

Most individuals, however, perform aerobic exercise on cycle ergometers without prior physical training. It has been shown [47, 56] that muscles such as the quadriceps muscle only have 1 or 2 Kg force in paralyzed individuals as little as 3 months after paralysis. Therefore, the muscles are so weak that it is hard to engage in a proper fitness program on a cycle ergometer without some type of prior training. If no weight training is done prior to cycle ergometry, the

increase in muscle force (fig 6) of the quadriceps is only a few Newtons over a 6 week period, while endurance barely reaches 30 minutes at the end of 6 weeks while cycling 3 times per week (fig 7). In contrast, if weight training is accomplished by exercising with 4 sets of 10 lifts, 3 days per week, for the quadriceps, hamstring and gluteus maximus muscles for 2 weeks prior to the onset of cycle ergometry, the initial endurance for cycling is higher as shown in figure 7 and muscle strength starts and increases much more rapidly during cycle ergometry as shown in figure 6. The greatest benefit of prior training is when weight training is accomplished for 6 weeks prior to cycle ergometry. Weight training for 6 weeks causes initial strength to be 115 Newtons on the 4 subjects shown in figure 6. Unlike the subjects endurance which is only a few seconds with no prior

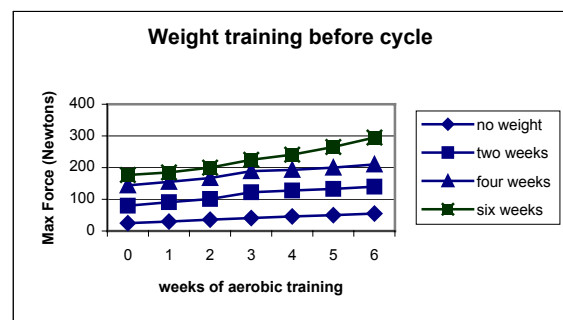


Figure 6. This figure illustrates the maximum force (in Newtons) that can be sustained during electrical stimulation of paralyzed quadriceps muscles in four subjects with a complete spinal cord injury after up to 6 weeks of aerobic training on FES cycle ergometer. 4 6 weeks of ergometer training accomplished 3 time per week, subjects engaged in a weight training program for 6 weeks (squares), 4 weeks (diamonds), 2 weeks (small squares), or had no prior weight training program at all (lower trace).

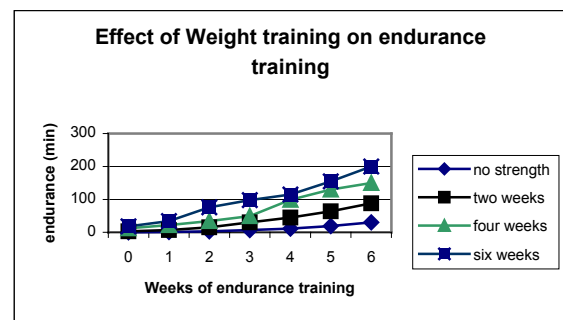


Figure 7 – This figure illustrates the effect of a prior weight training program on endurance time for cycling an FES cycle ergometer during 6 weeks of endurance training. Prior to the FES cycle ergometer program, weight training either no prior training was accomplished (lowest trace) or weight training was accomplished for 2 weeks, 4 weeks, or 6 weeks.

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weight training, initial endurance after 6 weeks of weight training is over 15 minutes.

The amount of work that can be accomplished on a cycle ergometer lies on training and the software. Recent evidence shows that by using an adaptive controller for the timing of stimulation of the muscle groups taking into consideration both pedal position and speed, work output and hence conditioning can quadruple [42].

Cardiovascular stress

One problem associated with cycle ergometry and electrical stimulation of paralyzed muscle for anaerobic weight training, however, are changes in blood pressure and heart rate. It is normal during exercise for blood pressure and heart rate to change. For example figure 8 shows the change in blood pressure (in kilopascals) as a percent duration of fatiguing isometric contractions at 40% of the strength of the quadriceps muscle in 6 individuals with complete spinal cord injuries (quadriplegia) where contractions were elicited by electrical stimulation. As can be seen in figure 8, blood pressure increases linearly throughout the duration of the contraction by 50% or more at the end [41, 52]. Part of the increase in pressure is due to reflex activation of sympathetic afferents causing powerful splanchnic constriction in the face of the small increase in cardiac output [41, 52]. However, some of the increase in blood pressure has been attributed to activation of skeletal muscle afferents that evokes the release of glutamate in the subretrofacial nucleus of the brain [23]. These areas of the ventrolateral medullary neurons then are intimately involved in part of the blood pressure raising reflex to exercise [5]. Obviously, in an individual with a complete spinal injury, the brain has little role and the blood pressure reflex is only peripherally mediated [41, 52]. However, the increase in blood pressure associated with electrically induced exercise can cause a problem for people with a compromised myocardium due to cardiovascular disease [41]. Aging potentiates this response. As shown in figure 9, for example, the maximum systolic and diastolic pressure increase significantly with age during electrically induced exercise. Further, as shown in figure 10, if an individual has hypertension during a fatiguing isometric contraction both systolic and diastolic blood pressure increase in proportion to the resting pressure. In other words, as shown in figure 10, the higher the resting pressure, the higher the maximum pressure at the end of exercise. Thus hypertension and age may place individuals doing exercise elicited by electrical stimulation at risk for aneurysms or stroke.

Heart rate, as shown in figure 11, is actually reduced with age. As shown in figure 11, the maximum heart rate during a fatiguing isometric contraction induced by

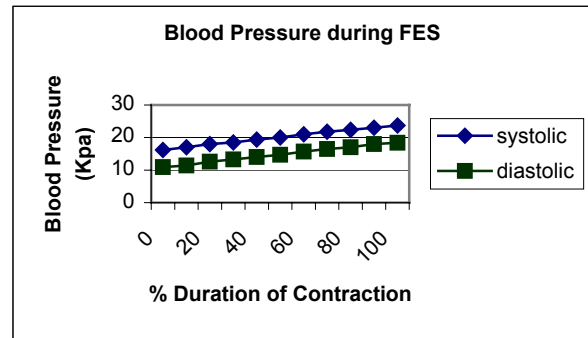


Figure 8. This illustrates typical systolic and diastolic blood pressure responses during a fatiguing isometric contraction induced by electrical stimulation of the quadriceps muscle in 4 patients with paraplegia. Blood pressure in kilopascals is shown as a percent duration of the fatiguing contraction at 40.

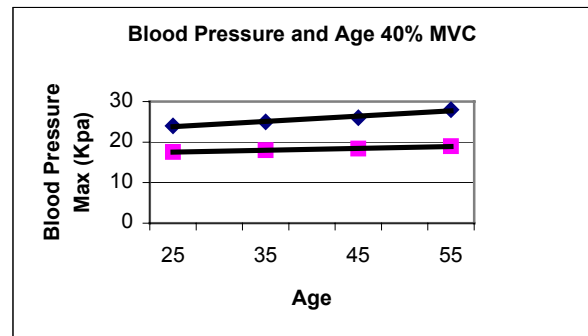


Figure 9. This figure illustrates the effect of the age of the subject on the maximum blood pressure (systolic = diamonds and diastolic = squares) during a fatiguing isometric contraction at 40% of strength induced by FES of the quadriceps muscle.

electrical stimulation is reduced substantially with age. Thus in the face of an increased blood pressure, cardiac work increases dramatically with each beat associated with age, hypertension, and fatiguing exercise.

Other risks

There are other considerations as well. Osteoporosis is common after neurological injury [49]. Fractures and soft tissue injuries have been reported during the use of electrical stimulation and therefore precautions for osteoporosis should be taken [49].

In summary then, electrical stimulation can be a dramatic way of increasing strength and endurance in paralyzed muscle, or even in non paralyzed muscle. However, caution should be noted in terms of pain, discomfort, and the potential for inducing a cardiovascular incident in individuals with a compromised myocardium or high blood pressure.

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Electrical stimulation for functional movement

Electrical stimulation can also be used for increasing functional movement. Electrical stimulation can be used for recovery of tendonesis grip [22] an upper arm prosthesis [39] or for ambulation in paralyzed individuals [25]. Electrical stimulation can be a powerful therapeutic modality for restoring hand function, or with the appropriate use of electrodes for the major muscle groups to restore ambulation. Several different modifications of these techniques for restoring ambulation have been developed. These include stimulating reflex activity during walking or

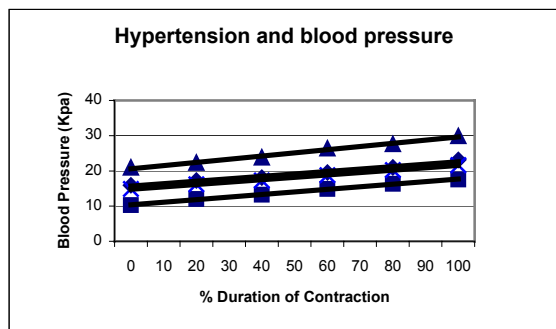


Figure 10 – This figure illustrates the effect of hypertension on the maximum blood pressure response in subjects who were paralyzed with a complete spinal cord injury during electrical stimulation of their quadriceps muscle at 40% of the muscles maximum strength. Illustrated here is the systolic (triangle) and diastolic (diamond) pressures in patients with resting hypertension compared to control subjects with no resting hypertension, whose systolic is shown as an x and diastolic as a square. The blood pressure is shown throughout the duration of the fatiguing isometric contraction % of the muscle's maximum strength and is expressed in kilopascals.

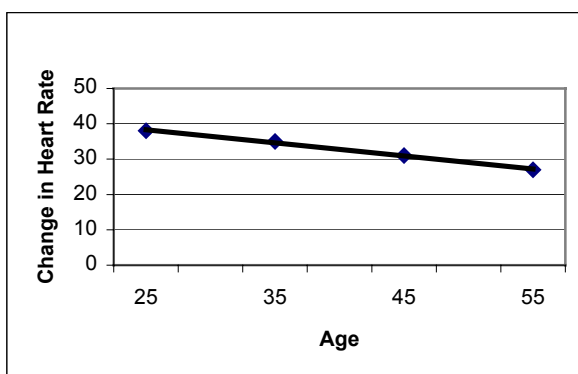


Figure 11 – the change in maximum heart rate associated with age in subjects with a completed spinal cord injury during electrical stimulation of the quadriceps muscle at 40% of the muscle isometric strength.

implantable wire electrode system [25]. Because of the extensive analysis in safety in the use of these systems, ranging all the way from osteoporosis to other potential medical complications, the use of electrical stimulation for hand function and ambulation will not be discussed in this article.

Electrical stimulation in conjunction with biofeedback therapy for restoring movement

One tool commonly used to train patients is called biofeedback or neuromuscular reeducation. This technique uses a measure of some physiological parameter such as the electromyogram to provide feedback to a patient of incorrect behavior [9, 12, 14]. For example, following stroke, the use of the electromyogram as a biofeedback modality has proven very effective to reduce spasticity and increase volitional control [8, 13]. The success of such a technique depends on proper operant conditioning protocols. [29, 38, 66].

Electrical stimulation can also be used in conjunction with EMG biofeedback to restore muscle function more effectively. Figure 12 shows an investigator working with an individual with quadriplegia to try to restore arm and wrist function where volition control is minimal. In figure 13, it can be seen that the strength of the biceps muscle was quite low at the beginning of biofeedback therapy (lower trace). With biofeedback alone, it increased slowly over a period of 5 weeks. However, when biofeedback is used in conjunction with electrical stimulation, electrical stimulation strengthens the muscle while the biofeedback is used to retraining motor control and the increase in muscle strength and endurance is much more dramatic as shown in the upper trace of figure 12.

Use of electrical stimulation for wound healing.

As mentioned above, electrical stimulation has gained wide spread acceptance as a method of healing hard to heal bone fractures. But in addition, electrical stimulation can be used for wound healing. Pressure sores are a common medical problem. In individuals



Figure 12 - Investigator using EMG as a biofeedback modality for neuromuscular reeducation.

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with a spinal cord injury, for example, the incidence of pressure sores is over 30% per year [56]. The incidence of pressure sores during hospitalization from stroke is over 21%. After hospitalization from stroke, the incident is equally as high [65]. In elderly patients, discharge from a nursing home without stroke, 41 % develop pressure sores. In a survey of home health care agencies, the incidence of pressure sores was as high as 41% of the clients [28]. Even pregnant women in hospitals have been shown to be susceptible to pressure sores. Even more frustrating is the development of diabetic ulcers in patients with diabetes. Diabetes is a major health care problem affecting millions of Americans alone every year [72]. The prevalence is 5.9% of the population, or in America today 15.7 Million people (CDC 2002). Almost 200, 000 people die each year from diabetes (CDC 2002). A common problem with diabetes that seems to be interrelated to all other complications is damage to small blood vessels. The damage to pre-capillary circulation has been analogous to premature aging of the microcirculation [67].

Electrical stimulation has often been used as a means of healing both types of wounds. In many studies it has been shown that the incidence of pressure sores in individuals with spinal cord injuries is reduced if a program of electrical stimulation is used to exercise paralyzed muscle [56]. This may be attributed to an increase in circulation associated with electrical stimulation. Akers and Gabrielson [1] found that high voltage galvanic stimulation, even without functional exercise, could increase the rate of healing of decubitus ulcers. Feedar et al [15] found that chronic dermal ulcers healed more quickly with Monophasic pulsed electrical stimulation. Franek et al (1999), found that Microcurrent direct DC stimulation also helped heal pressure sores, but high voltage galvanic stimulation gave the best result. Yarkony et al [71] reviewed a

number of studies where electrical stimulation was used to prevent pressure sores and found inconsistent results on the best stimulation parameters to use.

The mechanism for the effect of electrical stimulation on pressure sores appears to be related to the fact that bacterial growth is inhibited with electrical stimulation. Rowley et al [64] found that low level Microcurrent could inhibit bacterial growth especially for e-coli, a bacteria commonly associated with the inhibition of healing in pressure sores. Other studies have found that either the reduction in pressure sore incidences could be related to increases in circulation or increases in angiogenesis associated with electrical stimulation of wounds. Little is known in terms of the most efficient use of electrical stimulation [18, 44]. Much needs to be done to correctly understand the effect of electrical stimulation on wound healing.

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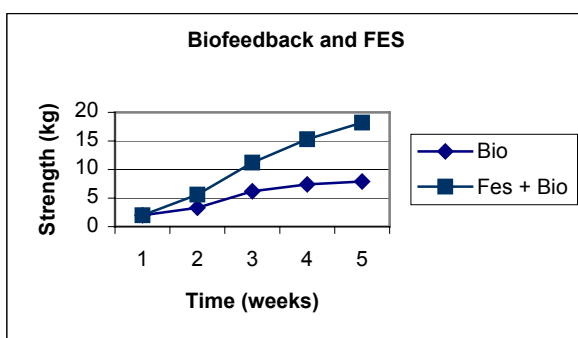


Figure 13 – This figure illustrated the gain in muscle strength during a 5 week session of either biofeedback, as illustrated in figure 11 (diamond), or a combined session involving biofeedback using EMG in the morning and electrical stimulation for increasing muscle strength in the afternoon (square) Figure 1

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