Adaptive control of functional neuromuscular stimulation-induced knee extension exercise

Bertram N. Ezenwa, PhD; Roger M. Glaser, PhD; William Couch, BS; Stephen F. Figoni, PhD, RKT; Mary M. Rodgers, PhD, PT

Institute for Rehabilitation Research and Medicine, Wright State University School of Medicine, Dayton, OH 45435; Department of Veterans Affairs Medical Center, Dayton, OH 45428; Rehabilitation Institute of Ohio, Miami Valley Hospital, Dayton OH 45409

Editor's Note:

This is the first in a series of three related papers in this issue on the subject of functional neuromuscular stimulation (FNS)-induced knee extension exercise. This article describes a newly developed exercise system from an engineering point of view.

The second article, "Acute Hemodynamic Responses of Spinal Cord Injured Individuals to Functional Neuromuscular Stimulation Knee Extension Exercise," by Stephen F. Figoni, PhD, *et al.*, describes and explains the acute physiologic responses to this exercise (*see pp. 9-18*).

The third and last paper, by Mary M. Rodgers, PhD, *et al.*, "Musculoskeletal Responses of SCI Individuals to FNS-Induced Knee Extension Exercise," on pages 19-26, discusses the exercise training responses.

Abstract—An automated system for exercising the paralyzed quadriceps muscles of spinal cord injured patients using functional neuromuscular stimulation (FNS) has been developed. It induces smooth concentric and eccentric contractions in both limbs to enable bilateral 70 degree knee extensions in an asynchronous pattern. External load resistance is applied at the ankle level to "overload" the muscles and bring about training effects. The system uses adaptive control methods to adjust FNS current output (threshold level and the ramp slope) to the quadriceps muscles to maintain performance as the muscles fatigue. Feedback control signals for limb movement and knee extension angle are used to continuously adjust the FNS current parameters so that the external load is moved through the preset

zero to 70 degree angle range. Typically, the threshold current level and the FNS current increase as the muscles fatigue to maintain performance with repetitive contractions. Fatigue is defined as the inability to extend the knee to 50 percent of the 70 degree target angle. When this occurs, FNS is automatically terminated for the fatigued leg, while the functioning leg continues to exercise. The automated nature of this system appears to be advantageous as compared to a manually operated system for subject safety, convenience, and uniformity of exercise bouts. Simulated safety problems, such as hyperextension of the knee joint, open circuitry, muscle spasms, and low battery power, were successfully detected by the logic circuitry, and the system followed appropriate safety procedures to minimize risk.

Address all correspondence and requests for reprints to: Bertram N. Ezenwa, PhD, Department of Rehabilitation Medicine and Restorative Care, Wright State University Research Center, 3171 Research Boulevard, Kettering, OH 45420. This work was supported by the Rehabilitation Research and Development Service of the Department of Veterans Affairs.

Key words: *adaptive stimulation control, functional neuromuscular stimulation (FNS), knee extension exercise, muscle performance, paralyzed quadriceps muscle, spinal cord injury (SCI), therapeutic exercise.*

INTRODUCTION

Most individuals with spinal cord injury (SCI), as well as those with other neuromuscular impairments caused by damage to the upper motor neurons, experience lower-limb muscle paralysis. The resulting lower-limb disuse can lead to secondary muscle atrophy and bone demineralization. Functional neuromuscular stimulation (FNS)-induced exercise has been shown to be effective in improving the strength and endurance of paralyzed muscles (7,8), and FNS techniques may ultimately be used to enable the performance of some daily activities (6,9,12,13,15,16). In the past nine years, several FNS systems which utilize closed-loop feedback control principles have been developed for knee extension (KE) exercise training of the paralyzed quadriceps muscles of SCI individuals (5,8,17,21). Although closed-loop feedback control of FNS current is advantageous over manual control with respect to automaticity and precision of muscle performance, these systems did not address changes in the FNS threshold current level that occur when the muscles fatigue with repetitive contractions. Maintaining threshold current at a constant preset level can cause marked and progressive delays in limb movement and loss of precision. It is also necessary to increase FNS current at a higher ramp rate with fatigue, in order to recruit additional muscle fibers at a faster rate to compensate for the ones that lose performance capability.

To better understand the performance characteristics of FNS-induced contractions of paralyzed muscles, studies on the FNS current versus fatiguing dynamic and static contractions of paralyzed muscles were conducted (2,3). These studies indicated that the FNS-induced contraction of paralyzed muscles may have nonlinear and possibly time-varying response characteristics. This is most likely due to the need to recruit functional motor units as others fatigue. Other investigators have made similar observations (1,10,11,14,18,20). Thus, to elicit smooth contractions and control of paralyzed muscles, the FNS control system should account for the changing characteristics of stimulated paralyzed muscles with various states of fatigue. The control system should be able to adapt to the changes in threshold current and stimulation intensity level required with each contraction in order to reduce delays in leg movement.

The purpose of this paper is to describe an automated FNS system for SCI individuals which can be used to induce smooth KE exercise of both legs in an asynchronous pattern. Movement is considered smooth if it satisfies the following conditions: 1) initiation of knee extension of one leg after the contralateral leg has reached the desired exten-

sion angle; 2) minimum or no delay in attaining threshold current values for FNS-induced contraction; and, 3) no sudden stops or abrupt leg movement. To achieve this, the system incorporates closed-loop feedback control with adaptive circuitry to alter FNS current parameters, as muscle fatigue progresses with repetitive contractions. This system can be used to increase the strength and endurance of the paralyzed quadriceps muscles for FNS applications, as well as to possibly increase knee range of motion and blood circulation.

METHODS

FNS-KE system description

Figure 1 illustrates the automated FNS-KE system. This consists of a specially constructed exercise chair with padded seat and back support, as well as mechanisms for adjusting the back support position for various femur lengths, stabilizing the knee joint, applying load weights to the lever arms, and for obtaining feedback signals via limb movement/position sensors for the adaptive FNS current control during KE exercise. As FNS current ramps up, the paralyzed quadriceps muscles contract concen-

Figure 1.

The automated FNS-knee extension system utilizing the adaptive stimulation control circuitry (ASCC). The positioning of the subject in the chair, the stabilization features, weight arm mechanisms, and ASCC control panel are shown.

Figure 2a.

Functional block diagram of the two-channel adaptive stimulator with the adaptive stimulation control circuitry (ASCC) for FNS-knee extension exercise.

trically to lift the lower leg of the subject and the attached load weights against gravity within a predetermined zero to 70 degree angle range. Then, the FNS current ramps down to return the limb and the load weight to the resting position via an eccentric contraction. This system utilizes limb movement/position feedback sensors in conjunction with adaptive control methods to adjust FNS current parameters in order to achieve the desired performance as the muscles fatigue. During each contraction, the FNS threshold current for movement is acquired and used to update (increase) this variable for the next contraction. To maintain performance with fatigue, the FNS current ramp is progressively increased nonlinearly by control circuitry. Progressive resistance exercise can be performed by placing additional weights on the lever arms as muscle performance improves. Logic circuitry detects muscle fatigue, spasticity, open electrode circuit and short circuit, and initiates appropriate system responses for subject safety.

In addition, mechanical dampers are attached to the weight levers to prevent rapid dropping of the legs if FNS control fails. This system has been successfully used to exercise-train SCI individuals to increase the strength and endurance of their paralyzed quadriceps muscles (19). Acute physiologic and musculoskeletal training responses of SCI subjects with this mode of FNS exercise have been evaluated and are presented in detail in separate papers (4,19).

Functional description of the adaptive electrical stimulator

Figure 2a illustrates a functional block diagram of the various subsystems of the adaptive stimulator for asynchronous FNS-KE exercise. Two channels (right and left) of FNS are provided. The function of each subsystem, and the interrelationship among subsystems are as follows:

Stimulator output/pulse generator. The right and left constant current amplifiers of the output stages continu-

Figure 2b.

Actual stimulation current output from the adaptive stimulator. Top tracing illustrates the stimulation current applied to the subject. Each horizontal major division represents 100 microseconds which translates into 300 microsecond pulse width. Each vertical major division represents 10 mV output from a current probe which is equivalent to 100 mA. Bottom tracing is similar to top tracing except that each horizontal major division is equivalent to 5 ms duration which approximates to 35 Hz pulse frequency.

ously receive monophasic pulses from a pulse generator at a frequency of 35 Hz and pulse duration of 300 microseconds. (This is illustrated in **Figure 2b**.) With input from the respective ramp generator and exponential generator, the constant current amplifiers convert the generator pulses into current-regulated stimulation output pulses, where the current output varies with the input drive amplitude. This current is fed into protection circuitry and it is applied to the subject via skin surface electrodes located over motor points of the quadriceps muscles in order to elicit KE exercise.

Ramp and exponential generators (R&EG). When the left or right R&EG stage receives a control signal from the control logic circuitry, it updates the FNS threshold current required to initiate movement of the limbs. In addition, an exponentially-ramped output wave is generated to recruit more muscle fibers as fatigue occurs. The choice of an exponential output ramp pattern was based upon the results of our previous studies on FNS current versus muscle performance characteristics (2,3). As the muscle fatigues, it requires more current to achieve the same level of contraction force as when it is non-fatigued. It was found that the current intensity required to achieve a given level of force output varies exponentially from the non-fatigued to the fatigued state. Since it is desired that the limb movement be relatively smooth, with minimum hesitation during onset of contraction, the muscles require an accelerated increase in FNS current. A linear output current ramp pattern tends to result in an excessively long time needed to complete the KE contraction cycle. The increasing threshold current value, as muscles fatigue, reduces the time lag for initiating leg movement.

Limb position/movement sensing. Right and left leg position/movement sensing potentiometers mounted upon the load-weight lever arms provide several types of information for adaptive control of the FNS current. Each supplies a voltage which is proportional to the angle between the load-weight arm and the vertical. The right/left potentiometer voltage feeds into a series of comparators to monitor limb position with respect to preset switching voltage values corresponding to 50 percent and 100 percent of the 70 degree KE target angle. The output of each of the position sensors also drives a differentiating circuit followed by another comparator. This arrangement provides information on when the limb movement starts. The information on the FNS current which produces the initial movement is stored in the threshold-capture and threshold-store circuitry.

Adaptive stimulation current control (ASCC). The ASCC receives all of its command signals from the master control system. When the stimulator system is first powered up, all variables used for FNS control (such as the threshold current value, position sensor voltage values, and the 50 percent and 100 percent KE conditions) are initialized, and the fault detect circuits are cleared. When the R&EGs are activated, the ASCC receives the same clearing signal from the master control system. This, in effect, cues the ASCC to release the preset threshold voltage to the R&EG to start at the expected FNS current value to initiate movement. During exercise bouts, this expected threshold current value is set to 90 percent of the actual threshold value from the

last contraction in order to provide smooth starts. When the leg starts to move, the position sensor immediately sends a signal to the ASCC. Since this indicates that the FNS has reached contraction threshold current, the ASCC captures and stores this threshold stimulation current value. This voltage is used to compute the next expected threshold value. As muscle fatigue occurs, the increasing threshold current reduces the time lag for initiating leg movement.

Master control system. The master control system performs the following tasks: 1) alternates the sequence of contraction from the left to the right leg and vice-versa; 2) sends a signal to the ramp generator to ramp current down if the knee extension reaches the target angle of 70 degrees, or if the stimulator output reaches a maximum of 150 mA; 3) discontinues FNS to a leg if it fatigues (i.e., if the knee extension does not achieve at least 50 percent of the 70 degree target angle, or if stimulator output reaches 150 mA), but, exercise of the functioning leg continues with the same timing as before; and, 4) shuts down the stimulator system when fatigue is detected in the second leg.

Safety features. The master control system also monitors the entire stimulator system, shuts it down if any of several fault conditions occur, and, a general indicator light comes on. This occurs with low battery power, an open sensor circuit, an open electrode circuit, and short circuits. Such malfunction protection helps ensure that no hyperextension of the knee joint or sudden jerky movements occur (which could be hazardous). Also, the system shuts down and the general fault indicator light is displayed if the R&EG continues to ramp up when the control signal indicates the opposite; and, if spasms occur which cause the knee joint to extend beyond the target angle of 70 degrees.

A microswitch-generated signal from the load-weight lever arm of the chair detects this condition, and the master control system forces the ramp generator to ramp down, with the FNS contraction resuming during the next cycle. The subject can also activate an emergency stop button to immediately shut down the stimulator system. There is also a provision for mechanical stopping of the load-weight lever arm just beyond activation of the hyperextension microswitch.

Along with the above-mentioned safety features which are built into the master control system, the stimulator system is battery-operated, thus eliminating ground loop problems. The design features the ability to use the same jack for battery charging and for providing power to the stimulator system from the rechargeable batteries. This eliminates the possibility of operator error in charging the battery from the line current while the system is in use.

RESULTS AND DISCUSSION

System performance

It was found that this adaptive stimulator system is quite effective for KE exercise training of most SCI individuals who respond to FNS. It is easy to operate since there are no adjustments necessary. The threshold current and the output current ramp are automatically set and continuously updated (with each contraction) in accordance with the muscle response characteristics and its state of fatigue. It provides smooth contractions that are uniform in characteristics, as operator subjectivity with respect to adjustments of threshold and output current ramp, are eliminated. Using this system with over 100 SCI individuals, no adverse effects or malfunctions have been experienced,

Figure 3.

Hypothetical illustration of the asynchronous nature of the knee extension exercise. Angle range versus time for a constant load-weight level are shown for the right leg (on top), and the left leg (at the bottom). Non-fatigued (I), moderately fatigued (II), and highly fatigued (III), conditions are shown. Cycle duration increases with fatigue.

thereby indicating its safety. This system can also be used for objective quantitative assessment of quadriceps muscle strength and endurance, which is necessary to evaluate the effectiveness of various FNS exercise training programs.

Asynchronous KE exercise versus time

Figure 3 provides a hypothetical illustration of the asynchronous KE exercise showing angle range versus time (at a constant load-weight level). The phase relationship between the KE for the right and left legs is set so that one leg begins to extend as the other leg achieves full extension and begins to return to the rest position. Three states of muscle fatigue are represented: I = non-fatigued; II = moderately fatigued; and, III = highly fatigued (i.e., target angle of 70 degrees is not achieved). As fatigue occurs with repetitive contractions, the time to perform the KE contraction cycle tends to increase. This is most likely due to the smaller number of functional muscle fibers and the decreasing absolute strength of the muscle. However, the exponential current ramp helps to compensate for the effects of fatigue and keeps the KE contraction cycle relatively short.

FNS current versus fatigue

Figure 4 provides a representative illustration (for a single leg and constant load-weight level) of the relationships between KE angle range versus time (A), and FNS current versus time (B). Four fatigue state conditions are illustrated: I = non-fatigued; II = moderately fatigued; III

= highly fatigued; and, IV = fully fatigued (i.e., 50 percent of the 70 degree target angle is not achieved). When the muscle is non-fatigued, it requires the lowest level of threshold current (T) to initiate movement.

System evaluation

Figure 5 (I-IV) shows actual data from a paraplegic subject (for both legs and constant load-weight of 15 kg) during system evaluation for conditions represented in **Figure 3** and **Figure 4**.

With repeated KE exercise, the threshold current tended to increase progressively. This phenomenon has been reported in previous papers (2,3), and it is most likely due to the need to recruit more muscle fibers to achieve movement. In addition, the non-fatigued muscle requires the lowest level of FNS current for the knee to extend through the full angle range. In this state, the FNS current ramp is almost linear. However, as fatigue progresses, the FNS current increases at an accelerated rate and the ramp becomes exponential. If the ramp characteristics did not change in this way, the KE cycle time would become prohibitively long, and lead to the early onset of fatigue. This FNS-KE exercise system provides smooth contractions of the quadriceps muscles and there is no apparent need for co-contraction of antagonist muscles. This is most likely due to the fact that the leg is secured to the weight lever arm and only moves in one plane. The chair is equipped with a mechanical damper to prevent the rapid dropping of the leg if the muscle control fails.

Figure 4.

Hypothetical illustration of the (A) FNS current versus time, and (B) knee extension angle range versus time. The load-weight is kept constant in A and B. Four fatigue states are shown: non-fatigued (I), fatigued (II), highly fatigued (III), and fully fatigued (IV).

Figure 5.

Actual data from a spinal cord injured subject illustrating the relationships between FNS current and time, and knee angle and time during four fatigue conditions (illustrated in Figures 3 and 4): I = non-fatigued; II = moderately fatigued; III = highly fatigued; and IV = fully fatigued (that is, 50 percent of the 70 degree target angle is not achieved).

CONCLUSION

From the results obtained by extensive use of this FNS-KE exercise system, we conclude that the adaptive stimulation current-control technique provides advantages over other closed-loop feedback stimulation systems previously described. We regularly obtain smooth, safe contractions from most SCI individuals, regardless of physical condi-

tion and the state of muscle fatigue. The effectiveness of this system for resistive exercise training of the paralyzed quadriceps muscles of SCI individuals, as well as the acute physiologic responses elicited, are reported in accompanying papers (4,19).

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