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Review: Functional electrical stimulation (FES) for mobility in human spinal cord injury and in muscle spasm and atrophy rehabilitation in horses

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Abstract: *Functional Electrical Stimulation (FES) is utilized in both human and equine medicine to improve muscle quality and function. When stimulation parameters of these two published applications are compared, differences are evident. The main use of FES for human spinal cord injury (SCI) patients is to assist in standing, walking and sitting activities, reduce muscle atrophy and/or spasms and to improve blood flow in the paralyzed muscle. One primary limiting factor in the successful progress of the patient is early onset fatigue, as well as asymmetry in movement. The main use of FES for horses is to improve muscle symmetry, reduce muscle spasms and atrophy as well as reeducate muscle memory with progressively stronger muscle contractions. One primary limiting factor is the slow speed of the muscle contractions, which does not mimic equine performance. The transfer of horse FES parameters to human SCI physical therapy protocols may be of assistance to: 1. Improve spinal and limb symmetry while also assisting in reducing the frequency of muscle atrophy and spasms; 2. Elicit progressively stronger muscular contractions to induce functional movements of associated joints to improve endurance. The transfer of human FES parameters to horse injury rehabilitation and performance enhancement may be of assistance to: 1. Quicken the reaction time of muscle contractions; 2. Improve the speed of muscle contractions over time.*

Keywords: *Horse, equine, SCI, stimulation parameters, protocols*

Introduction

The multiple uses of functional electrical stimulation (FES) technology have been discussed in the literature for decades. This paper will compare the parameters of two applications of FES; 1. In human medicine for: Spinal cord injury (SCI) patients during standing, walking and sitting; The reduction in muscle atrophy and spasticity and; The improvement in blood flow. 2. In equine injury rehabilitation and performance enhancement for: The improvement in muscle symmetry and muscle endurance; The reduction in muscle spasm and atrophy and; The reeducation of muscle memory. A comparison of the research and clinical results of the two FES systems shows that each system has been effective for their specific applications. The purpose of this paper is to discuss similarities and differences between the systems and to propose that a combined use, at different times during the FES protocols, may improve clinical outcomes.

FES human and horse system comparisons

The basic differences between the human and horse FES systems are as follows:

<u>Human FES parameters</u>
Overall stimulation parameters
Stimulation frequency: 25-30Hz quadriceps and gluteus; 50Hz peroneal nerve
Stimulation pulse width: 600µs (300µs + 300µs)
Pulse shape: Constant voltage biphasic symmetric rectangular pulses, with no pause between positive and negative phases

Electrode design: self-adhesive disposable electrodes
- Standing/Sitting - 2 channels, 4 electrodes, each leg
- Stepping/Walking - 2 channels, 4 electrodes, each leg; plus 1 channel, 2 electrodes over the peroneal nerve

Standing and sitting training
For standing, 2 stimulation channels (4 electrodes) on each leg are positioned on both the quadriceps and gluteus muscles. The ramp up to the preset stimulation intensity is about 0.8-1 second (depending on the patient). The ramp for sitting is longer in duration than for standing, to achieve a slower and "softer" sitting down motion. Stimulation of the quadriceps and gluteus muscles for standing and sitting produces only a direct muscular response, and is not used to produce a reflex flexion of the knee and hip.

Stepping and walking training with parallel bar assistance
For eliciting electrically activated stepping, initially the stimulation of the quadriceps and gluteus muscles of the non-supporting leg is switched off. The period of time the signal is off is based on the timing of the individual's swing phase, which is typically 0.8-1.5 seconds.

The peroneal nerve is then stimulated to obtain dorsiflexion of the foot and which also produces a reflex flexion in the knee and hip that initiates the swing phase. To obtain the swing phase of the stride, a third independent stimulation channel on each leg produces a short stimulation burst of 1.5-2 seconds in duration, without ramping, and the stimulation frequency for this channel is 50Hz. This specific stimulation combination produces a quick activation of the peroneus and anterior tibialis muscles and induces a reflex flexion in the hip and knee.

At the end of the swing phase, stimulation of the quadriceps and gluteus muscles are activated again to obtain the tension needed for stabilization of the leg for standing.

Research on the use of FES in humans
With the research on FES in humans for complete spinal cord injury, Dr. Helmut Kern and his group has shown positive effects over the past decades to:

- Prevent/revert muscle atrophy/degeneration (Kern, 2014)
- Reduce spasticity (Doucet et al, 2012; Hofstoetter et al, 2014)
- Generate standing and stepping-movements to improve walking speed, distance and improvement of cardiovascular fitness and metabolism (Kern et al, 2014; Graupe et al, 2008; Stöhr et al, 1985; Holle et al, 1984)
- Encourage lower extremity blood flow (Kern 2014).

In addition, there are no lower- or upper-time limits to begin a training program based on FES so the training can begin at anytime after the lesion has occurred and still be effective. (Kern et al, 2008; Graupe et al, 2008). FES has also been used successfully in the long-term therapeutic treatment of foot drop after stroke. (Dunning et al, 2015)

<u>Horse FES parameters</u>

Overall stimulation parameters
Stimulation frequency: 60 Hz
Stimulation pulse width: 500µs + pause (250µs + 250µs)
Pulse shape: Constant voltage biphasic pulses with two symmetric half waves (charge compensated) and pause in between pulses.
Electrode design: 3 channels, 6 electrodes, asterisk pattern of stimulation

Reduction in muscle spasm and atrophy
To reduce muscle spasm and atrophy in horses, the voltage is gradually increased over the 3 stimulation channels until a strong muscular contraction is produced, resulting in spinal or joint movement. Typically, this functional movement is obtained with an intensity of 6-8 volts. The production of functional movement can occur during the first treatment, or it may take several treatments, depending on the severity of the muscle spasm or atrophy. The electrodes are placed evenly on each side of the spine and the major goal is to obtain symmetrical functional movement with smooth and consistent contractions of the targeted muscles and associated joint(s) while the horse is standing.

Reeducation of muscle memory
Treatment time is 35 minutes which produces 525 cycles, to achieve the repetition of movement needed to help reeducate muscle memory. Treatment times are spaced close together in the initial stages with treatments typically being given every day or every other day for 2-3 weeks. At times when the response to the FES treatment is minimal, more than one treatment is given to the same area on the same day.

Research on the use of FES in horses
Specific research on the use of FES for horse rehabilitation has been performed over the past several years. Studies have shown that FES training for horses is a safe treatment that provides clinical improvements in equine epaxial muscle spasms (Ravara, 2015a; Ravara 2015b; Schils, 2015; Schils and Turner, 2014; Schils, 2013). FES training has also been shown to produce a positive effect on mitochondrial density and distribution in equine epaxial muscle, which in turn may help create healthier muscle tissue, that is better able to function during exercise (Schils et al, 2015). Preliminary data showing an improvement in the symmetry of the multifidus muscles of horses after 8 weeks of FES is an encouraging step to show empirically that changes in symmetry are also possible with FES training. The use of FES for horses has been able to produce quick and fairly dramatic changes in muscle tissue. Figure 1 shows the change in muscle atrophy over a period of 9 days with the application of 5 FES treatments to the infraspinatus and supraspinatus muscles, and 2 treatments symmetrically applied across the spine to the thorax region.

Discussion

A comparison of the two FES protocols for human and horse therapy illustrates some distinct differences, most markedly the pause between the positive and negative waves. The reasons for these differences is due to the variation of the outcomes of the two FES therapies. In humans, the purpose is to activate paralyzed muscle for sitting, standing and walking activities. In horses, the purpose of the FES stimulation is for injury rehabilitation and performance enhancement.

The human FES parameters for SCI uses short "bursts" of signal on and off to elicit the appropriate combination of support and swing phases of the limb producing dynamic movement. In addition, the peroneal nerve is stimulated individually to obtain dorsiflexion. In the literature, which discusses the parameters of human FES systems, frequency, pulse width and duty cycle vary a lot but commonly 20-50Hz, 300-600μs and cycles of 1:2-1:3 are used respectively (Doucet 2012). FES parameters should be tailored to the individual client's needs to reproduce normal activation patterns, optimize force output and reduce fatigue. In humans, home-based therapy in the individual's private environment is increasing rapidly and therefore it is hard to accurately evaluate and record outcomes when compared to a stationary/laboratory setting as practiced in the majority of horse therapy. In addition, the activities of daily living, and personal limitations and effort, cannot be influenced as easily with humans when compared to horses.

In the horse, the stimulus is always used for non paralyzed muscle and this is a distinct difference between the horse and human protocols. One of the short-term effects of horse muscle stimulation may be due to the consequences of reflex activity of the non paralyzed muscle, which is the result of sensory stimulation. To obtain the desired outcomes in horses, functional joint movement is obtained while the horse is stationary. In most cases, the signal crosses the spinal column and is symmetrically applied, however treatments to specific unilateral muscle groups is also performed.

Typically, during the first several FES treatments to the horse, the joint rotations obtained are not biomechanically correct. This incorrect movement pattern of the joint, which is most frequently observed as a lateral twist, illustrates the outcome of asymmetrical muscle development, As FES treatments progress over time, the joint rotation becomes more and more mechanically correct. Clinical observation after several treatments reveals an improved movement pattern in the horse resulting in better balance and performance.

The treatment area over the epaxial muscles of the horse is about 60 cm in length, and the specific area of the topline which is stimulated is changed periodically to target different muscle reactions. Observation of the movement patterns obtained with a variety of placements of the electrodes, trial and error, and observation of results over the past 20 years has refined the treatment protocols. Changes in the movement patterns of the muscles can happen quickly, and this could be due to several factors. One is that the horses are ambulatory so they move around most of the day keeping the muscles active. Horses lay down for only short periods of time so the muscles are constantly stimulated to a certain degree to support the mass of the horse. Second, a series of physical exercises are used to supplement the changes in movement patterns obtained by FES training, and in horses where the rider follows these exercises in combination with FES training, the improvements in the horse have an increased possibility of being quick and long lasting.

An improvement, which may be useful for human FES training outcomes, would be to increase muscle endurance and improve muscle symmetry in SCI patients through the use of horse FES training. In addition, the longer time frame of the horse FES treatment protocols could assist in the re-education of muscle memory and improve blood flow over an extended period of time.

One of the improvements that could be made in the horse FES training outcomes is to mimic the short bursts of activity required in equine performance, since the current stimulus pattern is based more on muscle endurance enhancement. This ability to improve the "quickness" of the muscle reaction time could prove to be a valuable addition to the horse FES protocol, especially for performance enhancement. In addition, increasing the speed of the muscle contractions could also improve the overall outcome of the horse FES training protocols by improving the variety of muscle responses, again better mimicking actual performance. The utilization of the human FES parameters would be useful for these purposes.

The use of the horse FES parameters to obtain stronger and stronger symmetrical muscle contractions over time, which more closely resembles functional movement, is an important element to the success of the outcome. If these stronger contractions are used in SCI patients for a longer period of time, care must be taken that the skeletal and soft tissues can withstand these intense contractions. A gradual increase in the strength and length of time of the contractions is essential for a positive outcome to occur. However, if the stimulus is not strong enough to elicit functional movement, then the full benefits of FES training are likely diminished. In addition, the use of the asterisk design of the horse FES parameters may help to vary the stimulation area and could prove a useful addition to the human protocols.

Conclusions

A discussion of the uses of FES in humans for SCI, and for horses rehabilitating from injury or for performance enhancement, has shown distinct differences between the parameters of the two modalities. The stimulation of paralyzed muscle in SCI patients where the sensory reflex is not present is different from the stimulation of non paralyzed muscles in horses where the sensory reflex is present. In addition, the main purpose of human FES is for short “bursts” of muscle activity for sitting, standing and walking. In comparison, the use of horse FES is mainly for improvements in muscle symmetry, the reduction in muscle spasms and atrophy, and for muscle re-education.

Could the FES parameters used for improvement in muscle function in humans and horses be combined to improve outcomes? The use of the horse FES parameters in human SCI physical therapy may be of assistance to: 1. Improve spinal and limb symmetry while also assisting to reduce frequency of muscle spasms and atrophy which occur during early and long-term disuse; 2. Elicit progressively stronger muscular contractions to induce functional movements of associated joints, while sitting, to improve endurance and increase blood flow. The use of the human FES parameters during rehabilitation from injury and for performance enhancement in horses may be of assistance to: 1. Shorten the reaction time of muscle contractions; 2. Improve the speed of muscle contractions over time.

A review of the similarities and differences between the human and horse FES has shown distinct and varying benefits of each protocol. It is intriguing to hypothesize that the combination of human and horse FES protocols may be useful in improving outcomes of both species. Future research must be performed to explore if the combined usage of the two types of protocols proves to be valuable.

References

Kern H. Functional Electrical Stimulation on Paraplegic Patients. Eur J Transl Myol. 2014 Jul 8; 24(2): 2940.

Doucet BM, Lam A, Griffin L . Neuromuscular electrical stimulation for skeletal muscle function. Yale J Biol Med. 2012 Jun;85(2):201-15.

Hofstoetter US, McKay WB, Tansey KE, Mayr W, Kern H, Minassian K. Modification of spasticity by transcutaneous spinal cord stimulation in individuals with incomplete spinal cord injury. J Spinal Cord Med. 2014 Mar;37(2):202-11.

Graupe D, Cerrel-Bazo H, Kern H, Carraro U. Walking performance, medical outcomes and patient training in FES of innervated muscles for ambulation by thoracic-level complete paraplegics. Neurol Res. 2008 Mar;30(2): 123-30.

Stöhr H., M. Frey, J. Holle, H. Kern, W. Mayr, G. Schwanda, H. Thoma. 20 channel implantable nerve stimulator makes paraplegic patients walk again. Proceedings, 14th Meeting of the Neuroelectric Society, International Symposium on Biomechanics of Muscle, Vravrona-Attica, Griechenland, 51, 1985

Holle J., M. Frey, H. Gruber, H. Kern, H. Stöhr, H. Thoma, J. Functional electrostimulation of paraplegics (experimental investigation sand first clinical experience with an implantable stimulation device). Orthopedics, 7, 1145-1155, 1984

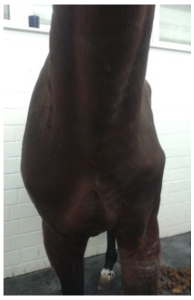
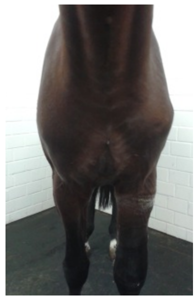


FIGURE 1. Seven FES treatments to the shoulder and thorax of the horse over 9 days



Kern H, Hofer C, Mödlin M, Mayr W, Vindigni V, Zampieri S, Boncompagni S, Protasi F, Carraro U. Stable muscle atrophy in long-term paraplegics with complete upper motor neuron lesion from 3- to 20-year SCI. Spinal Cord. 2008 Apr;46(4):293-304.Dunning K, O'Dell MW, Kluding P, McBride K. Peroneal Stimulation for Foot Drop After Stroke: A Systematic Review. Am J Phys Med Rehabil. 2015 Aug;94(8):649-64.

Ravara B, Gobbo V, Carraro U, Gelbmann L, Pribyl J, Schils S. Functional electrical stimulation as a safe and effective treatment for equine epaxial muscle spasms: Clinical evaluations and histochemical morphometry of mitochondria in muscle biopsies. Eur J Transl Myol - Basic Appl Myol 2015a;25(2):109-120

Ravara B, Gobbo V, Carraro U, Gelbmann L, Pribyl J, Schils S. Mitochondrial density and distribution by histochemical approaches distinguish muscle fiber types and support clinical improvements due to FES as a treatment of equine epaxial muscle spasms. Eur J Transl Myol/Basic Appl Myol 2015b; 25 (3): 145-182 (149) CIR-Myo News: Abstracts of the 2015 Spring Padua Muscle Days, Terme Euganee Padua (Italy), March 12 - 14, 2015.

Schils S, Carraro U, Turner T, Ravara B, Gobbo V, Kern H, Gelbmann L, Pribyl J. Functional Electrical Stimulation for Equine Muscle Hypertonicity: Histological Changes in Mitochondrial Density and Distribution. J Equine Vet Sc 35 2015a;907–916.

Schils SJ. Functional electrical stimulation (FES) use in horses for musculoskeletal and neuromuscular rehabilitation. Eur J Transl Myol/Basic Appl Myol 2015; 25 (3): 145-182 (148-149)CIR-Myo News: Abstracts of