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Case Report

Functional Electrical Stimulation (FES) in the Diagnosis and Treatment of Musculoskeletal and Neuromuscular Control Abnormalities in Horses - Selected Case Studies

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ABSTRACT

When diagnosing neuromuscular injury and pain, the use of biomechanical evaluations to assess the mechanics of movement patterns has been useful in the human population. Functional electrical stimulation (FES) is a technology that can create action potentials to produce musculoskeletal movement that is almost indistinguishable from the voluntary kinematics produced by the nervous system. To create controlled and precise musculoskeletal movements in humans and in horses, FES has been shown to be effective. In humans, the kinematic information obtained from FES data has been utilized to direct further diagnostics, and/or to assist in the development of specific treatment protocols. In addition, since FES creates dynamic movement while in a static position, the ability to isolate the regions of dysfunction improves without the confounding factors of over-the-ground movement and other artifacts caused by environmental stimuli. This paper explores the transfer of the use of FES in human diagnostics to clinical use in horses. Three equine case studies discuss how FES was employed as a tool in the diagnosis and treatment of equine musculoskeletal and neuromuscular control disorders.

1. Introduction

The procedures used in human musculoskeletal and neuromuscular control examinations to diagnose dysfunctions are elaborated in many research papers [1,2]. Interestingly, the muscular examination procedure in equine veterinary medicine is similar to that in human medicine [3–5]. Our aim in this paper is to highlight, through the presentation of several case studies, a dynamic diagnostic procedure utilizing functional electrical stimulation (FES) which has proven useful in diagnosing complex musculoskeletal problems in humans [6–9] and may also be useful in horses. In addition, we present information to support the application of FES in the treatment of musculoskeletal and neuromuscular control dysfunctions of the horse.

During an examination for dysfunction, the equine patient's posture and balance, muscle strength and flexibility, joint mobility, and localized swellings are observed and evaluated. Gait analysis is also used to obtain over the ground dynamic information which assists in the diagnostic processes. Static and dynamic examinations of the horse utilize pain perturbation, which focuses on signs and symptoms of the disorder, with a horse that is not always compliant with the procedures. In addition, due to the strong influence of environmental conditions on the horse, it can be challenging to accurately diagnose a neuromuscular dysfunction, especially when comparing observations over time.

Functional electrical stimulation (FES) produces action potentials in both nerves and muscle that are almost indistinguishable from those generated by the nervous system [10–16]. Human research has shown that the musculoskeletal movement patterns created by FES mimic voluntary muscle function and FES has been used extensively to create and maintain healthy muscles in spinal cord injury and stroke patients for decades [17–28]. The application of FES has been shown to improve healing outcomes in these populations when compared to other modalities or to just physical therapy alone [29–32]. In addition, re-education of muscle memory has also been a result of FES [33]. A study evaluating the long-term

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Animal welfare/ethical statement: The authors have adhered to the Principles of Veterinary Medical Ethics of the AVMA.

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effects of a FES protocol showed that spinal cord injury patients had sustained improvement in muscle function even after the discontinuation of its use [34,35].

To the healthy individual, the muscle contraction from FES feels almost identical to a voluntary muscular contraction [36–39]. For example, the neuromuscular synchronization during walking is mimicked through the walking pattern produced by FES in normal subjects [40–42]. Therefore, movements created by FES can be evaluated as representations of voluntary functional movements. In addition, with the patient in a controlled clinical environment, the environmental influences caused by changes in footing, clothing restrictions, or even muscular tension of the patient as a result of manual palpation, to name just a few, can be reduced. Incorrect diagnosis of neuromuscular control problems can occur when the patient consciously changes the native muscular movement, such as reducing spinal slump or foot pronation during walking, because the patient is aware that this positioning is not desirable. These voluntary "self-corrections", which frequently occur during examinations, could be reduced when the movement is obtained through FES.

FES has been used in horses for over 20 years to create vertebral and articular joint movement and has been shown to successfully improve some neuromuscular control disorders as well as improve muscle tone and symmetry [43–46]. In addition, the movement patterns created by FES in the horse have been confirmed to be similar to the movement created by manual vertebral manipulation [47]. Therefore, the value of FES movement as a representative of voluntary muscle function is compelling. However, it is important to note that the use of a physiologically appropriate electrotherapy waveform found in FES is essential to not only obtain the appropriate motor neuron activation but to improve compliance by the horse [48]. The authors feel that a clearer representation of the true neuromuscular and musculoskeletal responses is obtained in the horse through the use of FES to generate movement when combined with traditional lameness examinations and movement evaluation techniques.

The focus of this paper is to discuss: (1) The current research supporting the use of FES as an effective tool to improve muscle function. (2) How clinical use of the information obtained through the evaluation of the movement created by FES can be utilized in the dynamic diagnosis of neuromuscular control and musculoskeletal problems in the horse.

2. Technical Specifics of Functional electrical stimulation

Functional electrical stimulation is the transcutaneous application of an electrical current typically through surface electrodes to produce a controlled neuromuscular response. A microprocessor generates a train of impulses, which imitate the neural signals that pass between the spinal cord and the sensory and motor nerves in healthy muscle, producing a muscle contraction [49]. The intensity of the muscle contractions is controlled by the voltage applied and the specific muscles which are activated are determined by the placement of the electrodes. Stimulation which produces individual muscle movement is not the purpose or goal of FES, rather activating the groups of muscles that are necessary to produce functional movement is the focus of FES. A balanced waveform, which does not produce an accumulation of ions, is an essential specification of FES. To have a biologically correct electrotherapy signal "the delivered charge is extracted out of the targeted tissue at the end of every single stimulation pulse" [50]. This distinctive waveform is an important element when evaluating the long-term safety and effectiveness of FES, especially in cases of continual use such as for neuroprosthesis

FES has been researched extensively as a means to improve muscle function and tonicity by replicating voluntary or reflex muscle activity [51–53]. FES has been shown to reduce atrophy, decrease muscle spasticity, reduce inflammation and scar tissue, re-educate muscle function, strengthen muscles and tendons and improve bone-tendon junction healing [54–60]. Histological studies of spinal cord injury (SCI) patients, evaluating the use of FES for over 10 years, found a decrease in damaged fibers and an increase in functional fibers [61]. As a further aid to healing, FES has been shown to increase the size of myofibers and excite regeneration of new myofibers [62]. The use of FES has been proven to not be detrimental to nerve reinnervation after injury and in addition, this study also found that the FES treatment group showed improved muscle strength and geometry when compared to controls [63].

In unhealthy muscle, the normal neuromuscular pathway is disrupted resulting in muscle function abnormalities and pain. The hyperexcitability of neurons produces muscle hypertonicity, which causes the muscle to constantly contract, resulting in pain and, over time, tetany [64]. FES will disturb this neural hyperexcitability, returning the muscle to balanced contraction and relaxation phases, therefore reducing pain [65]. In contrast, FES will also assist in re-establishing the disrupted neuromuscular pathway in atrophied muscle [34,41,52,53,59,62].

When FES is utilized at higher voltages, the contractions of the muscle groups produce coordinated limb or body movements that are almost identical to the joint movements observed in the functional coordination of muscles needed to perform a task [39,50,51,66,67]. FES can therefore obtain a neuromuscular control response that is biologically functional, giving the therapy its name. The depolarization and repolarization of muscle fiber membranes by FES produces regional vertebral and joint movement patterns not only by the muscles but also by the associated tendons and ligaments. In comparison, other classes of nerve and muscle stimulators do not produce coordinated functional muscle contractions and obtain only an unorganized tremor or a twitch in the muscle being stimulated. Rough, quick, and nonfunctional movement can be obtained by these electrotherapy systems with higher amplitudes, however, clinical comparisons have found the voltage needed is typically 10 times higher than the voltage required by FES to obtain functional movement.

3. The Use of FES as a Diagnostic Tool in Equine Medicine

Past research documenting the use of FES to improve neuromuscular control and musculoskeletal dysfunctions in the horse [43–47] has documented that the process occurs over time and that improvement was determined based on the objective changes in muscle hypertonicity and muscle symmetry. However, evaluation of the changes in movement patterns produced by FES requires an understanding of the correct spinal and joint biomechanics of the movement being evaluated. Therefore, a qualified practitioner must correlate the movement pattern with an appropriate diagnosis. FES is not a substitute for skillful observation. However, FES can assist in clarifying dysfunctions that are better observed during movement, as well as for complex compensatory issues, by helping to isolate sources of dysfunction or pain. Dynamic movement evaluation is always a valuable tool when examining horses, and FES allows the observation of dynamic motion in a controlled environment with reduced artifacts. In addition, the movement pattern is not presented once or twice but repeatedly during the 20 to 35 minutes treatment sequence, while the degree of movement is carefully controlled, offering the evaluator many opportunities to clarify the movement pattern observed.

The application of the FES signal is through a pad approximately 23" long and 17" wide which is fitted with 6-2" x 4" electrodes equally spaced along the length of the pad with 3 electrodes placed on each side of the pad. For the application of FES to the

neck, self-stick electrodes 2" x 4" are utilized with 3 electrodes on each side of the neck, for a total of 6 electrodes. The pad, or self-stick electrodes for the neck treatment, are placed so that the signal of the FES crosses the spine to produce, in normally functioning tissue, bilateral, symmetrical musculoskeletal movement. To begin an FES treatment, the intensity of the FES signal is increased slowly until mild contractions are felt or seen. The response of the muscle to the stimulation, observed by evaluating the degree and type of contractions under each electrode is noted. Some horses will show a steady contraction phase followed by an equal relaxation phase mimicking the timing of the signal of the FES system. In contrast, other horses will show distinct muscle fasciculations with no clear contraction or relaxation pattern in response to the FES stimulus. As the voltage is increased, and more motor units are activated, functional movement is obtained. When the stimulus is over the sacroiliac region, pelvic rotation is observed, extension and flexion (dorsal/ventral) movement is seen during stimulation of the thoracic region, and extension and flexion (dorsal lift and arch) is observed when the stimulus activates the cervical region. FES can also be applied to the shoulders and lateral thigh regions of the horse obtaining mainly adduction and abduction muscular responses.

For diagnostic purposes in equine practice, FES is mainly used over the thoracolumbar, lumbosacral, and cervical regions of the horse. Ultrasound video taken during FES stimulation at T17-18 has shown that the signal can penetrate to the depth of the psoas muscle. Any muscle dysfunction is determined through the observation of the degree of symmetry and the range of motion created by FES assists in the diagnosis of any muscular dysfunction. When FES is applied over the same region on multiple horses, similar movement patterns are observed between horses that have a healthy neuromuscular control response and musculoskeletal balance. When an abnormal movement pattern is displayed by the horse, such as pathological vertebral or articular rotation, hypermobility, hypomobility, or postural sway, the cause of this faulty movement pattern is further investigated.

In addition, the conductivity, or resistance, of the muscle tissue to the functional movement produced by FES can be evaluated to provide insight into the normality of the neuromuscular control response. A low conductivity value in relation to a standard voltage may indicate resistance in the muscle to the neuromuscular signal produced by the FES, therefore some tissue abnormalities may exist. These abnormalities may indicate a high degree of fibrin, a hypertonic muscle response, dehydration, or systemic muscle disease, bacterial, or viral or protozoal infection. Conversely, a high conductivity in relationship to a standard voltage can also indicate abnormal muscular activity. These voltage and conductivity relationships are anecdotal, however over 10,000 FES treatments during a span of almost 30 years form the basis for these observations and evaluations and further study of this phenomenon is intriguing.

When the pad is placed over the sacroiliac region, some horses will display an abnormal clockwise or counterclockwise twist of the pelvis during pelvic rotation rather than a symmetrical caudal/cranial sagittal balanced pelvic rotation. Human research has found that asymmetrical movement causes significant biomechanical alignment problems which is a strong predeterminate to injury [68]. Symmetry of motion is the foundation of biomechanically correct movement, and the correct movement pattern is a very important element of long-term pain-free movement [69].

In general, when the abnormal rotation of the pelvis occurs as a result of the FES stimulation, asymmetrical tonicity of the muscles is also typically present during palpation. Typically, the abnormal movement which is a result of the FES stimulation corresponds with the findings from other diagnostic procedures or imaging of that region. However, sometimes the movement abnormalities produced by FES do not match other diagnostic results, and this inconsistency suggests the need for further evaluation of the dysfunction.

FES treatments to the neck can also help reduce spasms and atrophy in the cervical spine region. Several different arrangements of the electrodes can be utilized and the decision of the placement of the electrodes are used based on the type of functional movement that is desired. The reaction of the neck muscles to the FES signal is similar to the functional response of the epaxial and deep muscles of the back. Some horses will display a rotational twist in their neck, as a reaction to the treatment, while other horses will show straight and balanced sagittal plane dorsal vertebral arching during FES. The two most common electrode placements for FES to the neck include the "short triangle" and "long triangle" setup. The short triangle places the electrodes between C3/4 and C6/7 and the long triangle places the electrodes between C1 and C7.

Specific sites in the shoulder area and the hindquarters can also be treated unilaterally by placing six self-stick electrodes on the targeted site. It is important to always treat both sides of the horse, with the electrodes placed in exactly the same position, to obtain an accurate comparison of the overall muscle symmetry and range of motion between the two sides. The difference between the voltage and conductivity values of the two shoulder or hindquarter regions, as well as the observation of the differences between the movement patterns, assists in the evaluation of the health of the neuromuscular and musculoskeletal functions.

Compensatory mechanics can create secondary or tertiary pain and/or injuries that compound the diagnosis of a primary site of dysfunction. The use of FES to create movement patterns helps to identify sites of dysfunction and/or pain which may or may not be in conjunction with the musculoskeletal disorder identified by other diagnostic procedures, imaging or gait analysis. When the region of restricted movement in a painful area is stimulated with FES, the horse will display repeatable and consistent resistance to this particular movement, providing valuable diagnostic information. Exploration of different regions of the horse with the FES to observe the symmetry, range of motion, and comfort of the functional movement created, is essential in gathering information about the relationships between pain and dysfunction for that horse. Sometimes the regions with the greatest degree of dysfunction are not the regions with the greatest degree of pain [70].

A unique function of FES as a diagnostic tool for the horse is that, even when the purpose of the FES is to gather neuromuscular control information, repeated use of the stimulation will re-educate the muscle to become more symmetrical [46] with reduced muscle spasms [43]. Sequential FES treatments will train the muscles to obtain less and less abnormal movement, and the evaluation of how quickly the movement patterns improve can also assist in the diagnosis of the severity of the musculoskeletal pathology.

4. Selected Case Studies

Three case studies will be presented to outline the clinical use of FES as a diagnostic tool in equine medicine. Separate tables for each case study outlines the coordination of the diagnostic and treatment procedures and includes videos of the FES treatments performed. The videos are examples of the treatment outcomes and may or may not be the specific horse discussed in the case study. The importance of a complete veterinary exam should be emphasized as a foundation to any muscular diagnostic work performed with the use of FES. In addition, FES as a treatment tool is best utilized in conjunction with traditional veterinary procedures and protocols.

4.1. Case Study 1

The first case is a 12-year-old mare that was an International Grand Prix jumper (1.60 m height). Table 1 compiles the details of the veterinary exams, veterinary interventions, FES treatments, response to FES treatments, and the movement exercises used during riding to help improve the overall balance and function of the horse. The following text is a summary of the rehabilitation protocol detailed in Table 1.

This mare experienced a fall during jumping where her front legs "scissored" with one leg positioned forward and the opposite leg positioned backward obtaining an abnormal degree of range of motion of both limbs. The initial veterinary diagnosis after injury was low grade sacroiliac pain, bilateral lower cervical facet joint synovitis and arthritis, thoracolumbar facet immobility with remodeling, bilateral subscapular fasciitis, and shoulder joint synovitis.

Approximately 2 weeks after injury, FES treatments were initiated. FES treatments to a correctly functional sacroiliac region of the horse produce symmetrical (right to left) sagittal plane longitudinal extension and flexion of the pelvis. However, in this horse, the FES produced a strong clockwise rotation of the pelvis which, in the experience of the authors, could indicate a unilateral postural support musculature dysfunction, probably to the iliopsoas region. Antidotal observations over several years of this specific type of asymmetrical pelvic rotation have found that if a unilateral muscle spasm is in the right lumbar region the pelvic twist during FES is clockwise. In addition, the lumbar spine of this horse displayed an exaggerated extension phase with a shortened flexion phase during the pelvic rotation produced by the FES. This type of asymmetrical and unbalanced pelvic rotation likely placed pathological forces onto the femorotibial joint and femoropatellar joint (stifle) regions of the hind limbs and during the FES treatment destabilization (collapsing) of the right stifle region was noted. At the beginning of each FES treatment to the pelvic region for the first 2 weeks the mare was uncomfortable (repeatedly stepped sideways, swished her tail, and lifted her hind legs). However, she gradually accepted the FES stimulus, and a more balanced extension/flexion movement during pelvic rotation was obtained by the end of each 35-minute treatment session. As the number of treatment sessions increased, this improvement in the pelvic rotation was sustained between treatments, and the initial discomfort dissipated.

Interestingly, the thorax region did not palpate as hypertonic as expected, due to the type of injury sustained, but the thoracolumbar region did show mild postural lordosis. FES treatment to this region produced no dorsal/ventral movement therefore no specific dysfunction could be noted, and the horse was relaxed during the initial FES treatments. Typically, during FES, strong dysfunctional movement in the pelvis is associated with hypertonicity in the thorax, but this association was not noted in this case.

FES treatments laterally to the right and left hindquarter regions separately found strong adduction of the right lateral thigh when compared to the left. This was most likely a compensation by the right hind limb to counter the excessive medial placement (relative to the sagittal plane) of the left hind which was observed under tack. In addition, during the swing phase of the right hind, the entire limb would abnormally displace laterally and then swing back medially before stance, giving the right hind limb a "bow-legged" appearance during stance.

During palpation, the right side of the neck in the region of C6/7 was hypertonic and showed a high degree of sensitivity to touch. During FES to the neck region, the horse was initially very uncomfortable during the first 2 weeks and twisted her neck during the FES treatments. However, resolution of the asymmetrical movement and the hypertonicity at the base of the neck occurred within the first month and the FES treatments then focused on the upper cervical region.

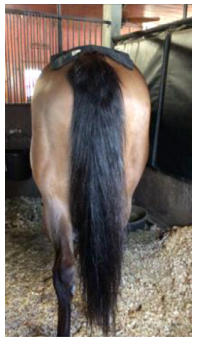
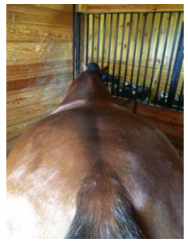
FES treatments separately to both shoulders found moderate muscular asymmetrical movement between the right and left shoulders. In addition, the right shoulder showed a lower conductivity value than the left shoulder at the same voltage, indicating greater hypertonicity of the right shoulder. Palpation of the right shoulder musculature was hypertonic when compared to the left which matched the results observed during the FES.

In summary, the FES found that the strong asymmetry between the left and right muscular function in the sacroiliac region during pelvic rotation, observed by the strong clockwise twist of the pelvis, and the unbalanced rotation of the pelvis with the longer extension phase when compared to the flexion phase, were the two primary dysfunctions. The destabilization of the stifle and the strong lateral displacement of the right hind during the swing phase were noted as outcomes of these two primary functional problems. The level of palpable pain was greatest in the shoulders and base of the neck but the strongest muscular asymmetry, based on the information obtained by the FES, was found in the shoulder region.

Exercises under saddle emphasized longitudinal (front to back) straightness in the swing phase of the hind limbs to reduce the pathological pelvic rotation and it was suggested to avoid lateral (side to side) bending exercises. During riding the left hind limb during stance was placed excessively medial of the sagittal plane in comparison to the right hind. This was counter to what occurs in most horses showing a clockwise pelvic rotation when, typically, the right hind is more medially placed. In addition, as noted previously, the mare showed an excessive lateral swing of the right hind before stance. This combination of abnormalities added to the assumption that multiple injuries probably occurred during the fall and several compensatory reactions were also most likely involved. However, the primary issue seemed to be in the region of the right pelvis, perhaps a right iliopsoas injury. If the right iliopsoas region was in spasm, the musculature would shorten on that side potentially creating other compensatory issues. This shortening of the right lumbar region musculature, when compared to the left, during riding was also observed. In addition, positioning of the horse's thoracolumbar spine into a more dorsal position was advocated during riding which typically increases the thoracolumbar longitudinal flexion (front to back) and therefore also results in less extension during pelvic rotation. The mare was encouraged to improve her longitudinal flexion by equally flexing the joints of her hind limbs and distributing her weight as caudal as possible, through a reduction in speed at all gaits. If shortening the overall stride length was required to reduce the speed of the gait, then that change was an acceptable outcome for this stage of the rehabilitation protocol. Ideally, the reduction of speed would occur as the suspension period of the swing phase of the stride was increased by lifting the hind leg higher, therefore, increasing the period of the stance phase of the opposite hind.

In view of the initial findings, during the next 2 months (21–50 days) of the protocol, veterinary interventions first focused on shockwave to the RH suspensory origin due to discomfort during hind limb flexions and clinical exam findings. FES work to the pelvic region continued to produce asymmetrical clockwise rotation, however, the degree steadily decreased. Once dorsal/ventral movement to the thorax was obtained, the mare showed a slight counter-clockwise lateral rotation that pushed the thoracolumbar region to the right. This change in rotation from the clockwise twist in the pelvic region, to counter-clockwise twist in the thoracic region, can indicate dysfunction in the thoracolumbar junction. In addition, this counterclockwise lateral rotation could be the reason the mare places the left hind medially, rather than placing the right hind more medial which would be a typical response to

Table 1
Case Study 1: Details of the veterinary exams, veterinary interventions, FES treatment sites, response to FES treatments and the movement exercises used during the physical rehabilitation protocol.

Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
Previous Month	12/28 Injury during landing from jump. "Scissored" with front limbs upon landing. Stride in front guarded through base of neck, tense through shoulders and subscapular region (despite recent treatment of subscapular region) Under tack: Bilateral short gait in front, not forward and reaching with stride. Flexions ok. Hind end trailing. Assessment after US and full clinical exam: Lower cervical facet synovitis and arthritis, bilateral, at c56, c67, c7t1. Shoulder joint synovitis. Bilateral subscapular fasciitis. Thoracolumbar facet remodeling and immobility. Si soreness low grade. Digital rads: cystic lesion with sclerotic margin at caudal c6 facet.	12/28 US guided inj lower cervical facets, selected lumbar facets and SI joints. Inj both shoulder joints and subscapular and withers inj focusing on left side. Follow up after chiro tx in 5 days, then recheck in 5 days in hand, then recheck 4 days under tack.					
20 days 1/11-2/1	1/11 Started FES program 1/24 Has been working, jumped yesterday. Subscapular and thoracic fasciitis history. Standing exam: Unhappy being touched. Feels ok over body. Joints quiet. Trot in hand: Moves evenly but a little tight. Under tack: Starts up short and restricted in front, underneath herself and not moving forward. Short and slight LF uneveness to the R in figure 8. After canter horse opens up appreciably to more flowing stride - not lame. Assessment: Getting better but not starting out good enough. Continue FES and flat work plan and jumping gymnastics to slowly ask horse to engage through body.	1/24	Si	4	6.2 222 Strong pelvic clockwise rotation (hips to R but thorax also falling R which is atypical of simple compensatory reactions). Some destabilization of R stifle during pelvic rotation. Lumbar region locked into extension. Uncomfortable.	 For video see Supplementary Materials 1-1 Clockwise twist may indicate a R side unilateral postural support musculature injury, maybe R iliopsoas region. Willingly accepts stimulus. Pelvic twist improves by end of tx session.	Hypertension t13-l6 producing mild visual lordosis. Lower R scapula compared to L.  LH strong medial placement in stance. RH strong abduction in swing phase due to excessive medial placement of LH under body. Therefore RH during swing phase must "swing wide" to clear LH in stance phase.

(*continued on next page*)

Table 1 (*continued*)

Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
			Thorax	2	7.2 222 Hypertonal, mild lordosis, No dorsal/ventral mvmt. But, comfortable during tx.	Difficult to determine indications of this reaction, but not normal to see strong dysfunction in si region and no discomfort during thorax tx.	 Hypertension c1-c7 and ascending pectoral. Riding: Focus on improving longitudinal flexion through entire spine. No lateral flexion if possible. Reduce curved lines. Position nose of the horse no lower than the base of the neck where the chest meets the neck. Must raise base of neck, withers and thorax at the same time. Mild RF adduction during swing phase. Do not allow horse to stretch frame too long, nor place neck too low. Must rock balance to hindquarters and slowing the tempo will assist with this. Because LH is too medially placed, LH must step laterally to L to allow "room" for the correct line up of R hind with R front. Work on changes of tempo during the trot and canter, then when those are balanced, add in transitions between gaits.
			Neck	2	6.8 121 Short triangle Uncomfortable, twisting neck, tense, hypertonal R base of neck. Improved acceptance by end of tx.	Hypertonal to the point that horse negatively reacts even to touch. Moderately uncomfortable during tx.	
			Shoulders	3	R 5.0 111 Hypertonal, strong adduction L 5.8 222 Normal, muscle contractions, balanced adduction/abduction.	Very asymmetrical response. Skeptical but accepting of FES stimulus in this region.	
			Hindquarters	3	R 5.6 222 Strong adduction and strong lateral roll of patella L 5.8 111 Relaxed, straight overall mild medial lean to R.	Accepts signal, not uncomfortable. Very asymmetrical between L and R hindquarter muscle activation. Much stronger R hindquarter adduction and strong lateral movement of R patella during adduction. Destabilization and collapsing of R stifle during pelvic rotations. In hand, strong lateral swing of RH before stance.	

(*continued on next page*)

Table 1 (*continued*)

Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
30 days 2/2-3/2	2/7 Has been jumping and returning to more normal training. Will proceed next week to full jumping. Standing exam: Feels generally good. Joints quiet. RH sus body and origin area somewhat full on palpation. Hoof testers negative. R hip area quiet. Trot in hand: No lameness. Flexions: All within normal. Induces discomfort. Ultrasound exam both hind sus ligaments. Generally good continue to increase training. Pressure over RH sus origin / upper body is mildly thickened on palpation. Both hind sus ligaments within normal. 2/21 Standing exam: Feels solid Trot in hand: No lameness clean gaits in straight line and circles. Under tack: Super. Minimal RF to the left. Flexions: Good. R lower neck stretch subtly makes RF freer. Assessment: Generally very good. Stronger. Happier. Keep on the plan.	2/7 Shockwave RH sus origin 800 shocks 35mm probe E6 later today, repeat twice more one week apart. Assess progress with feeling under tack of RH weakness. 2/21 No treatment.	Si/gluts	2/month	7.6 333 Still clockwise rotation but degree is smaller and pelvic rotation is smoother.	 For video see Supplementary Materials 1-4 Placed pad more caudal to encourage more pelvic flexion now that extension is improving. Rather than extending lumbar musculature horse moves into lumbar kyphosis, however then relaxes and extends lumbar musculature. More subtle but balanced pelvic rotation.	Continue to emphasize L hind positioned to L to keep LH and LF lined up. Can now focus on increased weight bear of RH since LH is not too medially placed. Do not allow R belly to fall R by keeping horse from leaning on R leg. Can now also add some lateral flexion work. Continue to focus on counter canter for straightness. Consider R half pass, counter canter to L (on R lead) as primary exercises. Keep L hip low and R shoulder up. Most likely base of R neck will be last area of forehand to function normally. Must extend base of neck up and out into contact of the rein or horse will not use topline muscles correctly. Continue to use transitions to help horse stay equally flexed in joints of hind legs. Then forehand can lighten and rider can reposition neck and shoulders for improved overall balance.
			Thorax	1/month	8.0 343 Very relaxed, mild dorsal/ventral movement only slight twist to R. Counter clockwise twist.	Surprisingly, thorax is the first region to show improvement in functional movement. This promotes the evaluation that the pathological pelvic rotation is more likely the primary dysfunction when comparing the thorax and si functional movement	
			Neck	1/month	7.8 333 Long triangle. Base of neck much improved in symmetry. Rhomboid hypertonal. Changed to long triangle position to activate musculature in poll region and encourage more cervical spinal traction. Uncomfortable in beginning, twisting neck, however quickly allowed stimulus to increase and relaxed mvmt.	Base of the R neck is hypertonal but not as functionally dysfunctional when compared to the rhomboid region of the neck.	

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Table 1 (*continued*)

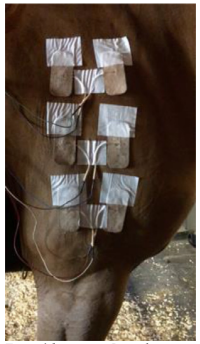
Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
			Shoulders	1/month	R 6.0 222 Strong adduction when compared to left. Less hypertonal L 5.8 222 balanced adduction/abduction.	 For video see Supplementary Materials 1-5 Shoulder adduction/abduction is noticeably different between R and L and could therefore be a more significant area of dysfunction than the thorax region musculature.	
			Hindquarters	2/month	R 6.6 333 Much straighter minor excessive adduction when compared to L. L 6.6 333 Straight, balanced adduction/abduction.	 For video see Supplementary Materials 1-6 Even though the musculature of the hindquarters appeared significantly different, the functional mvmt of the two lateral thigh regions of this horse are similar. This provides speculation that the lateral thighs are not a major region of mvmt dysfunction	

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Table 1 (*continued*)

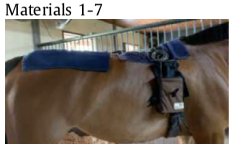
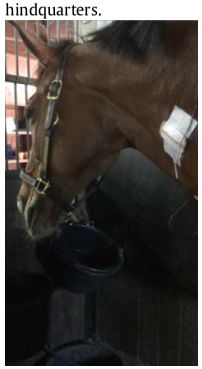
Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
30 days 3/3- 4/3	3/8 successfully jumped GP 3/22 Prep for large GP event Standing exam: Solid impression. Trot in hand: Slighlty wide gait behind, but not overtly lame. Trot circle asphalt: No lameness Flexions: R stifle slight. L stifle subtle. All others ok Assessment: Generally very good, low grade sciatica.	3/22 Inj both stifles and all four fetlocks. Caudal epidural inj to address sciatica.	Si/Gluts	4/month	6.4 333 Slight periodic increase in lumbar hypetonicity and clockwise pelvic rotation especially after competition.	Some loss of symmetry and use of the entire spine for longitudinal flexion. Overuse of lumbar musculature into extension leading to muscle spasms in that region. For video see Supplementary Materials 1-7 	LH generally lined up with L front at all times. Now able to encourage increased weight bear of RH by asking for equal flexion of all joints of hind limbs. Continue to work on more piaffe like trot steps. Improve balance in half-pass and do not allow to lean down on shoulder. Elevate forehand to reduce forces on forehand. Correct shoulder mvmt difficult to obtain, maybe more a shoulder muscle dysfunction issue than a neck issue? Add extended trot and canter, focus on keeping frame the same with horse just extending the length of the stride. Work on self-carriage for neck stability.
			Thorax	4/month	9.4 444 Excellent balance dorsal/ventral mvmt, straight, relaxed. However, some periodic lean to R. Counter clockwise twist.	Surprisingly, very good functional mvmt. Move focus from forehand mvmt dysfunction to hindquarter mvmt dysfunction.	
			Neck	2/month	8.0 444 Short triangle. Comfortable, relaxed.	Resolution of neck hypertension was much quicker than expected which redirectly focus to hindquarters. 	
			Shoulders	2/month	R 6.0 222 Strong adduction L 5.8 222 Balanced contractions.	For video see Supplementary Materials 1-8 R shoulder dysfunction could be involved in the hypertension found at the base of R neck.	
			Hindquarters	0		No treatments to this region due to improvement of functional mvmt in previous treatments.	

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Table 1 (*continued*)

Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
30 days 4/4-5/4	Travel for competition						
30 days 5/5-6/5	5/21 Feels generally excellent. Slight left neck immobility. Stifle joint synovitis low grade left more than right. Digital sheaths behind, both slightly full no active inflammation. Hoof testers negative. Walk in hand: RH rotates out and tends to land outside toe first. Trot in hand: Slight RH. Flexions: RH distal limb slight. R knee slight (on circle left). Trot circle asphalt: RH lame to the right. Diagnostic block RH Palmar digital nerve block: positive block - better on R circle asphalt. Longe soft ground - RF slow cranial phase to the left, slight. R knee flexion +. US exam RH distal limb: Small question lateral branch SDF but this may be from block. Repeat ultrasound on Wed without block in place. Assessment: Generally excellent review RH foot balance - rads show good medial - lateral balance, slight broken back axis of p123. Slight excess sole towards toe that could be trimmed to raise angles approximately 2 degrees. 5/23 Repeat US of RH SDF lateral branch - is acceptable with minimal change - monitor this and laser following jumping but the change is minimal and not an active problem. Also felt stiff to rider on previous day - review bloodwork / assess muscle health since stiffness may represent slow to recover. US exam Right dorsal colon thickened at 0.48 to 0.6 cm thick.	5/21 Consider inject hind coffin joints and hind digital sheaths, plus R carpus & carpal sheath pending rads and repeat US of RH. 5/23 Add misoprostol to current regimen of Alimend and Sucralfate - treat x 30 days only. Inj R carpus & carpal sheath Inj both hind coffin joints and digital sheaths.	Si/Gluts	5/month	8.6 444 Mild clockwise rotation.	Inconsistent, tension in lumbar region, kyphosis then relaxed and mvmt improved gradually over time.	Focus on opening elbows to help stabilize base of neck. This could also assist in reducing asymmetrical forces on the knees. Work on piaffe type trot to increase stance phase to improve hindquarter strength. This will reduce forces on forehand. Improve self carriage to improve forehand lightness through encouraging a higher neck and wither carriage without pressure into bridle.
			Thorax	4/month	9.6 555 Excellent, balanced, moderate dorsal/ventral mvmt. R shoulder adduction during tx.	Some clockwise rotation but quickly resolved. Then comfortable and relaxed.	
			Neck	1/month	7.6 202 Long triangle good cervical traction, comfortable.	Rhomboid region again hypertense. Slow, steady improvement. 	
			Shoulders	2/month	R 5.6 222 L 5.8 222 Overall, balanced adduction/abduction for both shoulders.	For video see Supplementary Materials 1-9 Initially L shoulder more hypertonal than R. Then stronger R shoulder adduction but mild. Atypically muscle spasms exchange between sides	
			Hindquarters	1/month	R 7.0 333 tighter than left but still good functional mvmt. L 6.8 333 steady contractions.	Surprisingly symmetrical overall even which increase in work load.	

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Table 1 (*continued*)

Case study 1 8-month protocol	Veterinary exam	Veterinary intervention	FES tx region	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES treatments	Biomechanical assessment and mvmt exercises during riding
Actively showing 60 days 6/6-8/6	7/10 Has been generally good. Standing exam: Subscapular immobility left more than right extending through upper thoracics (to t14). Mild stifle joint synovitis. Very quiet elsewhere. Trot in hand: No lameness Flexions: Subtle from stifles R more than L. All others negative. Under tack: Generally excellent. Outside hindlimb tends to be slow and wide (subtle) RH more than L. At trot and canter does not elevate through the withers as much as should. Thoracolumbar mobility is better to the L than to the R. Assessment: Generally very good. 1. Subscapular and withers tension 2. Low grade stifle joint synovitis. 3. Low grade thoracolumbar immobility - improving.	7/10 Subscapular and withers injection Continue FES therapy as needed. Add shockwave therapy thoracolumbars when possible.	Si/Guts	7/month	9.0 444 Great extension, smooth, straight! Still more extension than flexion and continued to be major focus.	Mvmt of pelvis producing dorsal/ventral mvmt into thorax. Much improved but still major area of dysfunction. Very comfortable. Future work will focus on increasing pelvic flexion.	Piaffe like trot. To emphasize flexion of entire hind limbs and improved pelvic flexion. Self carriage work to help correctly develop musculature of the neck specifically rhomboid activity at this point. Flying changes and lengthening of trot used to help improve shoulder reach.
			Thorax	5/month	8.8 555 Relaxed dorsal/ventral mvmt with periodic counter-clockwise twist that resolves by end of tx.	Clockwise twist appears to be related to pelvic movement dysfunction and is probably not a primary thorax region muscle dysfunction. Dysfunction is most likely tied to shoulder muscle dysfunction.	
			Neck	5/month	Short triangle 6.4 202 Rhomboid 6.8 111 Excellent overall symmetrical muscular response.	Very comfortable, quick resolution of muscle hypertonicity and asymmetry in this region. Base of R neck has not proven to be a primary area of dysfunction.	
			Shoulders	2/month	R 6.4 222 fussy, strong uneven muscle contractions. L 6.2 222 minimal muscle mvmt. Overall shoulders more symmetrical but still inconsistent improvement.	Shoulders are a continued area of concern. Cannot maintain improvement in muscular function without sustained FES to the region. R shoulder adduction is a continued area of focus.	
			Hindquarters	0		Hindquarter adduction/abduction appeared to be much improved so txs were reduced in this area.	

Abbreviations: FES – Functional Electrical Stimulation, Inj – Injections, L – Left, LF – Left front, LH – Left hind, Mvmt – Movement, R – Right, RF – Right front, RH – Right hind, SDF – Superficial digital flexor, SI - Sacroiliac, Sus – Suspensory, Tx – Treatment, US – Ultrasound

a clockwise lateral twist of the pelvis during rotation. Interestingly, the hindquarter region of the mare during this time became quite symmetrical showing a well-balanced activation of the adductors and abductors. The neck continued to improve in symmetry and range of motion, but the mare would initially show some discomfort to the stimulus then than would relax, perhaps due to the more cranial change in the position of the electrodes which was initiated at this time.

Riding exercises continued to emphasize lateral straightness by lining up the left hind with the left front but now added exercises to improve the weight bear of the right hind since the left hind stance phase position had improved. Specifically, these hind limb weight-bear exercises included increasing the number of transitions between the 3 gaits as well as transitions to lengthen and shorten the stride within the same gait. The right thoracolumbar region was positioned too far to the right which caused the right shoulder to exert strong right shoulder adduction to compensate. Therefore, exercises were now added to improve the function of the shoulders. The addition of some lateral flexion work (specifically to help reduce the strong adduction of the right shoulder) included leg yield, half pass (especially to the right), and counter canter (to left, on right lead) as primary exercises.

At approximately 3 months into the protocol the mare jumped successfully at the Grand Prix level and 4 weeks later traveled to Europe to participate in a large international competition.

Veterinary interventions (51–80 days) into the protocol before travel to Europe included treatments to address sciatica, both stifle joints and metacarpophalangeal and metatarsophalangeal (fetlock) joints. With the use of continual FES treatments, the symmetry of the pelvic rotation, during both FES treatments and work under saddle, improved. However, there were periods of time when the muscles, especially of the pelvic region and shoulders, became hypertonic and additional FES treatments resolved the resulting asymmetry and reduced range of motion. In addition, as the mare was able to better distribute her weight to her hindquarters and remain better laterally balanced, the hypertonicity in the shoulders and neck improved which was most likely due to the reduction of forces on the front limbs. FES treatments to both shoulders were necessary because of the continued strong adduction of the right shoulder. Surprisingly, the initial neck hypertonicity was a minimal long-term problem while the shoulders showed inconsistent improvement. Therefore, this could indicate that the initial "scissoring" injury affected the shoulders to a greater extent, even though initial palpations showed a higher degree of sensitivity in the caudal neck. Another possibility would be that a chronic issue in the musculature of the shoulder was present before the injury. FES treatments to the hindquarters during this period were not performed due to the quick improvement in function in this region.

After competition (111–200 days), veterinary intervention over the next several months included support treatments to the right carpus and carpal sheath, both hind coffin joints and digital sheaths, sacroiliac and lumbar spinal regions, both stifle joints, both subscapular areas, and the cranial thoracic (withers) region.

Upon return from the competition, some subscapular tension and cranial thoracic tension returned but were identified and quickly resolved with additional FES work. The FES treatments showed that, as the protocol progressed, the main muscular dysfunction became her lack of ability to correctly flex longitudinally during pelvic rotation and not remain in extension. In addition, she continued to not equally accept weight, nor flex, through all the joints in her hind limbs. In addition, the clockwise lateral rotation during pelvic flexion placed more forces on the right stifle as seen through the destabilization of the stifles during FES (especially of the right stifle) and this destabilization of the stifles was reduced when the pelvic rotation became more symmetrical. The mare returned to Grand Prix jumping full time and continues to compete at that level 3 years after the onset of the FES protocol.

In summary, FES was used as a diagnostic tool after injury to help identify a major dysfunction in the pelvic musculature. This dysfunction was presented as a strong clockwise rotation of the pelvis and a chronic hypertonicity in the lumbar region producing an abnormal degree of the lumbar extension during pelvic rotation. In addition, the asymmetrical forces in the stifles due to this incorrect pelvic region dysfunction, produced stifle destabilization. The initial high degree of palpable pain in the forehand, especially in the neck, was most likely a result of the injury of the "scissoring" fall but this discomfort resolved quickly. However, the asymmetrical musculature in the shoulder region remained a concern during even the later stages of the rehabilitation protocol. It was also established that when the mare reduced the forces on the forehand by raising the forehand during exercise, this allowed her to shift her weight caudally, and overall, the pain in the forehand resolved. However, the strong adduction of the right shoulder during FES, in comparison to the left shoulder, showed inconsistent improvement and needed periodic re-evaluation, and was not completely resolved by the end of the treatment period. In comparison, the neck dysfunction improved to the point that no, to minimal, treatment was necessary. As a result of this FES rehabilitation protocol, the pelvic and shoulder regions were found to be the regions of chronic muscular dysfunction and continued to be the areas primarily monitored.

4.2. Case Study 2

The second case is a 9-year-old Grand Prix jumping mare that had been diagnosed with sacroiliac and thoracolumbar discomfort when exercising, determined through the lack of willingness to flex laterally during changes of direction resulting in a "hopping" motion. Table 2 compiles the details of the veterinary exams, veterinary interventions, FES treatments, response to FES treatments, and the movement exercises used during riding to help improve the overall balance and function of the horse. The following text is a summary of the rehabilitation protocol detailed in Table 2.

No specific injury date was noted but the gait abnormalities had become more pronounced over time. The mare also displayed bilateral forelimb lameness and left hind lameness. The veterinary lameness exam identified moderate sacroiliac and thoracolumbar muscle tension, especially on the right side, with mild stifle discomfort, and ultrasound imaging identified synovitis of the cervical facets. Veterinary interventions included injections of both carpi, left shoulder joint and bicipital bursa, sacroiliac joints and left hind suspensory origin. Shockwave to the lower neck and left hind suspensory origin was also performed.

FES treatments were then initiated for 7 days consecutively to the thorax, sacroiliac, hindquarters and neck regions. The greatest degree of tension and pathological movement was determined to be in the sacroiliac region based on the muscular response to the FES stimulus. The pelvic musculature was locked into flexion and FES to this region produced a mild clockwise rotation of the pelvis resulting in a secondary destabilization of both stifles but was more pronounced in the right stifle. During the initial FES treatments, the mare was uncomfortable and would lean against the wall and rub her hips, step sideways and lift her hind legs. The thoracolumbar musculature also showed strong pathological hypertonicity and was locked into a mild dorsal lift giving the mare the appearance of kyphosis in the thoracolumbar region. The neck reacted painfully to palpation and initially, during FES treatments to this region, she was uncomfortable and consistently twisted her head and neck and rubbed her neck against the wall. Hypertonicity in the postural support musculature of the multifidi and iliopsoas was suspected due to the strong muscular spasms in the lum-

Table 2
Case Study 2: Details of the veterinary exams, veterinary interventions, FES treatment sites, response to FES treatments and the movement exercises used during the physical rehabilitation protocol.

Case study 2 14-month protocol	Veterinary exam	Veterinary intervention	FES tx site	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES txs	Biomechanical assessment and mvmt exercises during riding
Previous Month							
	1/7 Bilateral forelimb lameness to start and hopping in connection to the R. RF lameness to the L is the predominant lameness. Diagnostic block: L carpus upper and lower joints, improved 80% LF but still some LF lameness present especially to the R, which is worse following caudal shoulder flexion. Also LH lameness presents particularly going R, and worse with rider rising inside diagonal to the R. Horse is more even in front but not happy. Diagnostic block: Both front feet high Palmar digital nerve block: No change with firm ground, perhaps more open stride on soft ground longeing but no improvement under tack. Diagnostic block: LH sus origin directly, positive block. Ultrasound exam: Both fore within normal. LH sus origin periostitis proximal plantar cannon and some fibrosis (scar tissue) at the insertion - mild change, normal size. RH sus origin no periostitis and slight scar tissue - more typical “wear and tear” type change while there is bone activity LH. Assessment: bilateral carpal lameness significant, with LH sus origin periostitis. Sacroiliac soreness. 1/16 Trot in hand asphalt: No lameness Trot circle in hand asphalt: No lameness both directions - Looks great! Under tack: Head high and hind end trailing - posture of extension rather than flexion. Hopping in figure 8 especially after change of direction and more to the R than to L although today similar both directions. After canter notable improvement. Assessment: Still not feeling right. Postural weakness, attempt to manage with exercise program (discussed with trainer). Encourage horse to raise the withers and work in a lower frame through the neck. Examine weekly under tack through the process.	1/7 Rads both carpii Inject both carpii Inject left shoulder joint and bicipital bursa Inject sacroiliac joints Inject LH sus origin Shockwave lower neck and LH sus origin Shoe wide toe / narrow branch sus shoe, both hind.					

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Table 2 (*continued*)

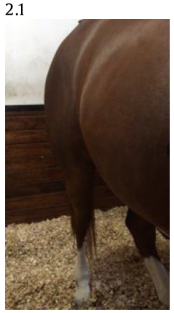
Case study 2 14-month protocol	Veterinary exam	Veterinary intervention	FES tx site	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES txs	Biomechanical assessment and mvmt exercises during riding
7 days 3/4-3/10	3/4 Started FES protocol FES treatments for 7 days consecutively treating 2-3 sites per day 3/8 Under tack: hopping at trot to the R is improved when rider keeps RF corner up keeping contact with L rein and by engaging LH. Diagnostic block of LH sus origin makes it easier for rider to access LH and reduces LH lameness apparent at trot R when rider rising with inside diagonal. Plan: FES therapy today, recheck under tack tomorrow. At appropriate time in future: 1. Shockwave LH sus origin, thoracics, and subscapular region. Continue shockwave LH sus origin once per week. 2. US guided inj lumbar vertebrae & si joints, caudal epidural injection, and inj LH sus origin local injection (again).	No treatments	Si/Gluts	4	11.2 666 Limited, tight rotation but generally straight. Lifting lumbar region rather than rotating pelvis. Mild clockwise rotation, tends to drop R hip with destabilization and medial roll of R stifle. Tense, some "parking out" to block rotation then relaxed by end of treatments.  For video see Supplementary Materials 2.1  For video see Supplementary Materials 2.2	Initially very tense, pelvis locked into flexion, but fairly straight, minimal rotation at end of first tx. After 3 days, positioned pad more caudal to increase flexion during pelvic rotation. Tense, restricted, asymmetrical mvmt at beginning, some destabilization of stifles, mainly right, improved after 7 days.	Counter clockwise thoracic rotation pushing rib cage to the R. R lumbar muscle spasms. Perhaps that is pulling the lumbar region to R. Discussion of possible postural support musculature injury of iliopsoas and multifidi due to strong postural lumbar kyphotic bracing and pelvic twisting during FES. R poll region muscle spasms, R ear higher than L. Riding: "Hopping" on RH. Unevenness of RF diminished when rider keeps R shoulder high and places more weight over to LH. Rider is encouraged to push R belly over to LH and keep more L rein contact to help horse's balance stay more over LH. Should feel like horse is always drifting to the L, regardless of direction. Half-pass L improved balance, especially in R turns. Very important to keep neck straight and raised to help rebalance weight to hindquarters. Keep tempo slower than horse prefers to encourage full weight bear of both hind legs and equal flexion of hind limb joints. Horse responded very quickly to changes in the balance in the under saddle work and became much more willing and comfortable. Was ridden 6x/wk. Significant reduction in lumbar muscle region kyphotic hypertonicity. Now that mvmt in the thorax and pelvic region are acceptable, the exercises to improve the mvmt of the shoulders canl be added.

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Table 2 (*continued*)

Case study 2 14-month protocol	Veterinary exam	Veterinary intervention	FES tx site	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES txs	Biomechanical assessment and mvmt exercises during riding
			Thorax	6	10.6 565 No dorsal/ventral movement, very tense, rubbing neck and later tail against wall. Strong R lumbar spasm. Very uncomfortable. 	No functional mvmt. Initially very tense, counter clockwise rotation of thorax (pushing belly R) then later rubbing neck and then tail during FES tx. Consistently leaning and stepping to R. Rubbing tail which could indicate sciatica involvement.	
			Neck	2	For video see Supplementary Materials 2.3 6.2 111 Short triangle. Very fussy. Twisting neck L and rubbing R neck against wall. However, mild asymmetries when functional mvmt occurred. 	Uncomfortable at beginning but allowed stimulus to continue. However, after 2nd tx neck straightened and some cervical vertebral traction was obtained, then relaxed.	
			Shoulders	0		Since the thoracic region was very hypertonal with no functional mvmt, FES to the shoulders at this time is typically not beneficial to the overall improvement in functional mechanics, therefore thorax and si regions were focused on for tx.	
			Hindquarters	1	R 6.0 111 Lateral roll of R stifle pushing hips to left L 6.0 212 More symmetrical adduction/abduction mvmt.	Difficult to determine usefulness of txs to this region due to the strong asymmetry and lack of range of motion of the si and thorax. Perhaps too early in the protocol to tx this region effectively.	

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Table 2 (*continued*)

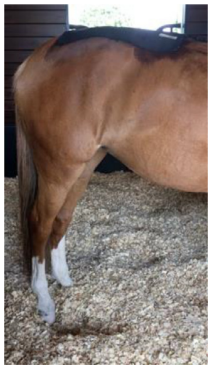
Case study 2 14-month protocol	Veterinary exam	Veterinary intervention	FES tx site	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES txs	Biomechanical assessment and mvmt exercises during riding
22 days 3/11-3/31	3/17 Under tack: starts out slight LH uneven and mixing a little in front. Standing exam: front fetlocks slightly active. Moderate sciatica. Stifle points + especially L stifle and moderate to mild joint effusion L stifle more than R Muscles of LH developing well and feel good. Assessment: LH stifle and sus origin play a role in LH weakness. Sciatica present moderate level deserves treatment. Both fore fetlock joints slightly active.	3/17 Inject both fore fetlock joints. Inject both stifles. Inject LH sus origin. Caudal epidural injection. Shockwave LH sus origin every two weeks.	Si/Gluts	2	10.6 555 Overall improved degree of pelvic range of motion. Note lower voltage than previously but greater degree of mvmt. No tail rubbing. 	Smoother, better balanced flexion and extension but pelvis still moving more easily into flexion. L gluteal spasm, could be a compensatory of R lumbar spasm.	Started jumping. Keep weight on outside hind leg especially tracking R. This rebalancing significantly helped to lighten forehand. Add pirouette feeling to turns, try pirouette into half-pass mvmts, especially to L to keep more weight on LH then horse can unweight RF and unevenness improves. Still difficult for horse to move lumbar region into extension but continues slow, steady improvement.
			Thorax	4	For video see Supplementary Materials 2-5 8.8 555 Still tense and fussy at beginning of tx still no dorsal/ventral mvmt.	L lumbar muscle spasm during tx.	
			Neck	1	6.4 222 Short triangle Excellent improvements in straightness and some mild functional arching of neck in response to stimulus. Relaxed.	Very surprising that the neck improved so quickly. Perhaps neck tension is an acute response to more chronic issues in other regions.	
			Shoulders	1	R 5.2 222 Comfortable, balanced adduction/abduction. L 5.2 222 Hypertonal, adduction with strong unbalanced contraction/relaxation phases.	Although volage and conductivity values were similar L and R, the muscle response was very different. Further tx to this region was therefore indicated.	
			Hindquarters	0		Since functional mvmt in si/gluts was limited, with inconsistent symmetry, txs focused on the thorax and si regions.	

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Table 2 (*continued*)

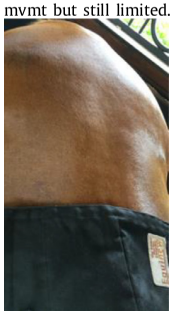
Case study 2 14-month protocol	Veterinary exam	Veterinary intervention	FES tx site	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES txs	Biomechanical assessment and mvmt exercises during riding
30 days 4/1- 4/30	4/4 Evaluation end of season. Wearing bar shim with open steel shoes with rockered toes. Feels very good overall. Lower neck and subscapular region quiet. Lower back mobile and quiet, well muscled. Stifles quiet. Hoof testers negative. Trot in hand: No lameness Flexions: All within normal Longe: Moves well. If minimally slow cranial phase of the stride to the RH end excellent.	4/4 Is in a good place. No treatment.	Si/Gluts	1/month	7.2 333 R gluteal spasm, perhaps a compensatory to L lumbar spasm. Lifting lumbar region rather than flexing pelvis. Almost symmetrical rotation.	Placed pad more caudal to produce stronger flexion in pelvis. Left lumbar spasm in previous treatments however right gluteal spasm which is typically a compensatory reaction.	Increase in number of days jumping and height of fence. Still maintaining slower tempo to encourage full weight bear of both hind legs. Maintain careful evaluation of horizontal straightness of pelvis and shoulders, especially as lateral bending is introduced back into the program. Important to keep forehand light and high to improve balance, especially through turns.
			Thorax	3/month	7.8 444 Slowly becoming more comfortable with some dorsal/ventral mvmt but still limited.  For video see Supplementary Materials 2-6	Becomes main area of concern due to lack of resolution of hypertonicity and limited, asymmetrical mvmt of thorax when mvmt is obtained.	
			Neck	0		Reduced focus on this region due to overall improvement in function.	
			Shoulders	2/month	R 5.0 222 Comfortable, balanced adduction/abduction L 5.4 222 fussy, stiff more hypertonal, stronger adduction.	Steady improvement in symmetry of muscle functionality between R and L shoulders but still asymmetrical.	
			Hindquarters	0		Considered again tx to this region but due to pelvic rotation improvement lateral thigh txs were most likely not necessary.	

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Table 2 (*continued*)

Case study 2 14-month protocol	Veterinary exam	Veterinary intervention	FES tx site	Number of txs during time frame	Average voltage and conductivity values and response to stimulus	Improvements observed with FES txs	Biomechanical assessment and mvmt exercises during riding
30 days 5/1-6/1							
	5/1 Standing exam: Feels great Joints quiet. Back nicely developed and much stronger. Withers symmetry and muscle much improved. Neck mobility is good. Trot in hand: No lameness, looks great Trot circles: No lameness, looks great. 5/21 Standing exam: Focal soreness R lower neck at c67 c7t1. Topline feels great otherwise. Hind coffin joints mild to moderate effusion and resents passive flexion hind coffin joints. Hoof testers negativek all 4, note frog pressure from pad support. Trot in hand: No lameness, carries RH a little wide and drifts to the L somewhat at the trot. Flexions: Within normal. Trot circle asphalt: Ok Longe soft ground: Short gait behind and does not bend well to the R, but not overtly lame. Clinical impression of hind feet (short) and R lower neck (not bending well). US exam both hind sus origins: RH within in normal limits. LH stress at plantar cannon – no active inflammation and similar to January images, with perhaps a little more "maturity" to the bone remodeling. Stable. Assessment: Some soreness lower neck R side.	5/1 Treatment: None 5/21 US guided inj lower cervical facets. Subscapular injection Inj both hind coffin joints (note copius watery fluid both hind coffin joints).	Si/Gluts	2/month	9.4 454 Rotation of pelvis symmetrical and smooth with good range of motion. Some twisting of hips L now overcompensation of correction? Then straight next tx.	Change in rotation direction, which could indicate that the body is also changing chronic functional movement patterns. This is typically a positive change but care must be taken to not over compensate.	After neck and shoulder inj (5/21), thorax became straighter and hindquarters more symmetrical, perhaps because mvmt from hindquarters was not blocked by forehand. Neck was surprisingly not hypertonal. Major area of muscular dysfunction was thorax and the shoulder regions so positioning the horse to lift the thorax was primary. Care was taken that the thorax does not roll to the R which then drops the R shoulder and then the LH cannot easily accept weight. Shoulder work to improve the strong adduction of the R shoulder could focus on half-pass (R more than L) and counter canter work. Lots of transitions within the gaits to keep the thorax stabilized and lifted.
			Thorax	4/month	9.0 444 Tense at beginning of month then relaxed as time went on showing moderate dorsal/ventral mvmt. Mild counter clockwise twist which indicated that evaluation of the neck musculature may be indicated.	Thorax was determined to be major area of dysfunction and symmetrical dorsal/ventral mvmt was finally obtained.	
			Neck	1/month	Short triangle 5.0 111 Excellent symmetry and functional movement, relaxed.	Tx to this region did not find muscular dysfunction.	
			Shoulders	1/month	R 5.6 222 Tense, strong adduction, then relaxed and balanced adduction/abduction L 5.8 222 balanced adduction/abduction.	Since thorax region continues to show muscular dysfunction, evaluation of shoulders was logical. Tension between the R/L shoulders changed from previous txs. Perhaps due to changes in overall body mechanics . Additional txs to the shoulders was indicated.	
			Hindquarters	0		Due to continued improvement in the symmetrical rotation of the pelvis, it was determined that tx to this region were not justified at this point. Txs to this region would certainly have no adverse effects. However, it is advantageous to consider the fewest overall txs necessary.	
Actively Competing 6 months							The horse traveled to Europe and on 6/15 won a large GP. Continued to compete successfully throughout the remainder of the year.

Abbreviations: FES – Functional Electrical Stimulation, Inj – Injections, L – Left, LF – Left front, LH – Left hind, Mvmt – Movement, R – Right, RF – Right front, RH – Right hind, SDF – Superficial digital flexor, SI - Sacroiliac, Sus – Suspensory, Tx – Treatment, US – Ultrasound

bar and thoracic regions, and pelvic twists during FES treatment, as well as the kyphotic positioning of the lumbar spine.

Exercises under the saddle during this time emphasized riding the horse with a more dorsally placed thorax and neck carriage than she preferred. Over several days, as the mare complied with the new position, she was able to better redistribute her weight caudally onto her hindquarters therefore most likely reducing the forces on the front limbs. This change in body carriage immediately improved the comfort of the horse. In addition, encouraging the horse to stretch the neck up and out helped to reduce the tendency of this mare to tighten in the lumbar region. When the horse would lower the neck below the point where the neck meets the chest, visually the lumbar region would tighten and shorten and position into kyphosis and the hind limb stride length would shorten. Once the kyphosis in the thoracolumbar region began to resolve, the hyperflexion in the pelvis also improved. It was suggested to avoid any lateral (side to side) bending so that the force distribution to the stifles was as symmetrical as possible. Equal flexion of the joints of the hindlimbs and extension of the thoracolumbar region was encouraged by adding exercises to slow the speed of the gait and encourage the hinfoot to completely contact the ground. Slowing the speed of all gaits was a major element of the improvement in this mare in her limb function due to the observation that she pushed off with her hind limbs with her toe pointed down and resisted full heel contact during stance. Specifically encouraging the horse to accept more weight onto the left hind heel significantly improved the evenness of the stride. Once the horse accepted weight onto the left hind limb then the ability to lighten the right front shoulder improved. It appeared that when the right shoulder was low the mare would not be well balanced, especially through turns.

During the next 3 weeks (8–30 days), veterinary interventions included injection of both front fetlock joints, both stifles, the left hind suspensory origin, and a caudal epidural treatment to address sciatica. FES work continued and the asymmetrical lateral rotation of the pelvis and the destabilization in the stifle region during pelvic rotation improved. In addition, the degree of the range of motion of the pelvis increased with the lumbar muscles showing a distinct reduction in kyphosis and she stopped rubbing her hips during the FES treatments to the pelvic region. The greatest hypertonic region was the thorax during this time. The difference between the left and right shoulders was also notable with strong left shoulder adduction in response to the FES, indicating the need to further investigate this asymmetry. The function of the muscles in the neck improved dramatically offering symmetrical functional movement in response to the FES stimulus.

During riding, jumping was added to the protocol and although it was still difficult for the mare to move the lumbar region correctly into extension, there was a steady improvement in the range of motion of the pelvis. The jumping seemed to help her extend the lumbar region better than working here on the flat. Riding focused on exercises that kept the forehand light by raising the neck and thorax and remaining attentive that the left hind carried as much weight as the right hind.

During the following month (31–60 days), no veterinary intervention occurred and there was continued improvement in the symmetry and range of motion of each region in response to the FES treatments. The two areas of most concern were the pelvic and shoulder regions since the resolution of the musculature hypertonicity and asymmetry was not obtained. Riding focused on maintaining a steady, slow tempo to continue to encourage the increased weight bear of the hind limbs while keeping the forehand light and reducing lateral flexion. The kyphosis of the lumbar region significantly improved and seemed to be related to the improvement in the symmetry of the pelvic rotation produced by the FES treatments.

During the next two months (61–90 days), veterinary treatments to the caudal cervical vertebrae and subscapular regions seemed to make the mare more comfortable. She began to jump higher and more easily lifted her forehand to clear the jumps. The shoulder region continued to show some muscular asymmetry and the thorax region was now a focus as well in an attempt to investigate if thorax treatments would assist in improving the asymmetry in the shoulder region. Riding continued to emphasize the lifting of the thorax and added the concept of “opening up” the shoulders during flat work and jumping to encourage a reduction in shoulder and thorax hypertonicity and lightness of the forehand. Exercises included half-pass work and counter canter.

About 6 months after the start of the rehabilitation protocol the mare traveled to Europe and won a large Grand Prix jumping competition. The mare continues to jump successfully in high-level Grand Prix competitions 2.5 years after the initial diagnosis with only limited follow-up veterinary and FES treatments.

In summary, FES as a diagnostic tool focused the initial treatments for this case on the pelvic and neck regions to address the potential postural support muscular hypertonicity. At the beginning of the protocol, the focus was on the thoracolumbar kyphosis and destabilization into the stifles resulting from asymmetrical lateral rotation of the pelvis. However, interestingly the long-term follow-up treatments changed the focus to the thorax with a secondary focus on the shoulders. It appeared that the intense initial pain in the neck was resolved once the mare was able to redistribute her weight symmetrically onto her hindquarters and the forces on the front limbs were reduced. Also, the stifle destabilization resolved quickly, and it appeared that this destabilization was only minimally contributing to the overall pathological biomechanics. When the mare redistributed her weight from her forehand specifically to her left hind this quickly improved her gait mechanics and reduced the discomfort in her neck and shoulders. Stretching her neck up and out allowed her to release the tension and reduce the kyphosis in the lumbar region.

4.3. Case Study 3

The third case is a 12-year-old Grand Prix jumping mare with had been diagnosed with a chronic active desmitis in the left hind medial suspensory branch injury. Recovery was poor during a 3-month conservative rehabilitation period of rest with hypertonicity developing in her spinal musculature and mild left stifle joint effusion. Table 3 compiles the details of the veterinary exams, veterinary interventions, FES treatments, response to FES treatments, and the movement exercises used during riding to help improve the overall balance and function of the horse. The following text is a summary of the rehabilitation protocol detailed in Table 3.

During the next month, FES treatments were initiated and surprisingly showed no significant dysfunction in the thoracolumbar or sacroiliac regions. Initially, the mare exhibited some resistance to the stimulus but a balanced movement pattern and a symmetrical response to the FES, common to normal musculature, was quickly observed. Interestingly, FES to the thorax region produced pelvic rotation which is unusual but is observed in horses considered to have an overall healthy, flexible spine, most likely due to the lack of regional muscle spasms which would then limit the movement of that section of the spine. To display correct biomechanical movement patterns in the spine while also displaying a high degree of lameness in the hind limbs is unusual in the authors’ experience.

FES stimulus to the adductor/abductor muscle groups of the hind limbs found distinct asymmetries suggesting that the cause, or result, of the distal limb lameness was due to abnormalities in this regional muscling. During riding, the mare would exhibit an exaggerated shortened left hind swing phase (both cranial and

Table 3
Case Study 3: Details of the veterinary exams, veterinary interventions, FES treatment sites, response to FES treatments and the movement exercises used during the physical rehabilitation protocol.

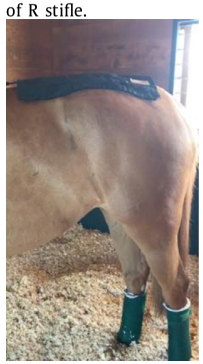
Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
Previous 3 months	3/9 History: Follow up LH. Has been walking under tack daily. Ionic are therapy daily. Shockwave. Laser. Pulsing ultrasound. Standing exam: LH medial branch palpates better, smaller, more organized but still thickened. US exam: Sus origin stressed fiber pattern. Medial branch diffuse injury as previously, trending toward improvement overall scar tissue surrounding the branch distally. assessment: chronic active desmitis LH medial sus branch with some remodeling at the origin as well.	1. Arterial limb perfusion stem cells tomorrow. 2. Laser and shockwave before the perfusion. Repeat arterial perfusion in 1-mo topical blister. Continue walk under tack. Turnout when feasible.					
36 Days 5-24	5/24 Started FES program 6/25 Evaluation. Has been progressing in FES and work program doing well. Standing exam: Impression of gaining strength overall. Stifle points slight left more than right and left stifle joint slightly full. Does not resent passive flexion of stifles. Hind fetlocks palpate stable and does not overtly resent passive flexion. Trot in hand: 1/5 lame LH. Flexions: both hind fetlock flexions increase lameness somewhat, LH more than RH. Trot circle: some mixing lameness behind, low grade. Assessment: Some stifle joint activity, low grade, left more than right. Not overtly weak through stifles at today's exam but if catching stifle continues, then internal blister may be appropriate.	No treatment	Si/Gluts	10/mo	7.8 333 Uneven extension/flexion, resting LH. However rotation was straight and improved quickly. Some destabilization of R stifle.  For video see Supplementary Materials 3-1	Quite straight rotations, but with limited range of motion. Locked in lumbar region, but quickly improved.	RH is too long of a stride when compared to LH. Slow down RH. Must also encourage more weight bear on LH to improve overall balance. Sitting trot helps this horse to slow tempo and better stretch lumbar region which resists extension during FES work. Steady improvement in evenness of length of stride over time period. Canter work began 6/18. Horse prefers to canter in warm up and canter seems to help to engage hindquarters. However, trot stabilizes thorax helping to engage hindquarter as well as lift forehand.

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Table 3 (*continued*)

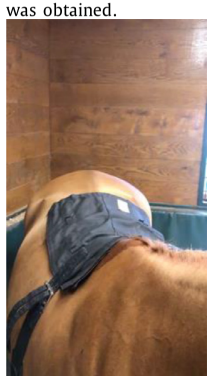
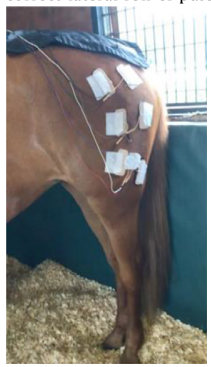
Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
			Thorax	8/mo	8.6 333 Limited dorsal/ventral mvmt, belly R with mild counter-clockwise rotation. However, very good mvmt thru spine into pelvis was obtained. 	Some hypertonicity, perhaps "blocking" the ability of the hind limbs to swing correctly under body.	
			Neck	2/mo	For video see Supplementary Materials 3-2 5.2 000 Short triangles tense, fussy no functional mvmt but contractions under all electrodes.	Hypertonic throughout, neck feels "jammed" and short.	
			Shoulders	0		No dysfunction was found during palpations and mvmt evaluations so determination was to wait to tx this region.	
			Hindquarters	5/mo	R 7.8 343 Fasciculations in quads, medial roll of the patella, locking stifle, overall better balanced adduction/abduction than L L 8.4 343 Strong adduction dropping L stifle, sway to L, correct lateral roll of patella.  For video see Supplementary Materials 3-3	Quite asymmetrical responses between R and L lateral thighs. Typically tx to the L lateral thigh produces sway to the R, however in this case sway was to the L.	

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Table 3 (*continued*)

Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
90 Days 7/1-9/30							
	9/4 Evaluation in hand. Has been making steady progress in work under tack. Standing exam; topline feels quite good. Both hind med sus branches thick and firm no pain on palpation but does resent passive flexion both hind fetlocks left more than right. Trot in hand: Short guarded and low grade LH lameness. Flexions: Positive response fetlock flexions both hind. Assessment: Slow progress. continue to move forward with work.	9/4 Support medial sus branches with therapies below: 1. Ionicare daily over medial sus branches both hind. 2. Laser all four sus branches 4 D per week, focus medial branches 3. Shockwave both hind medial sus branches 500 each and lateral 200 each e6 once per week. 4. Passive flexion hind fetlocks 2x daily 15–20 active flexion cycles each leg 2x daily (while standing in stall).	Si/GIuts	8/mo	9.0 454 Smooth, straight moderate rotation, extension phase improved.	Pelvic rotation is quite good when mvmt is isolated. Focus is more on improving thoracic dorsal/ventral movement.	Strides still uneven, must shorten right hind to even stride. RH is beginning to drift L and position too far under body. Also, R belly is too far R. Positioning haunches L interestingly helped to straighten right belly from drifting too far R. R base of neck is in spasm and must stretch correctly up and out to the right rein to help lengthen frame from poll to tail without falling on forehand. Needs more stability in neck especially during jumping. Started low jumping. Keep weight on outside hind in both directions to lighten forehand.
			Thorax	10/mo	6.8 333 Dorsal/ventral movement with mild counterclockwise rotation, belly still R, mvmt into pelvis. Note lower voltage with same conductivity produced more mvmt than previously.	Continued overall improvement. Also, produced excellent straight pelvic rotation, unusual to have these two areas function together.	

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Table 3 (*continued*)

Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
			Neck	3/mo	5.8 222 Short triangle steady, symmetrical contractions.	Relaxed, excellent traction and some arching of neck.	
			Shoulders	0		Considered tx to this area but decided to focus on lateral thighs since palpation and mvmt of shoulders appeared good.	
			Hindquarters	6/mo	R 7.6 212 Drift to L, locking stifle region, some medial roll but overall balanced adduction//abduction L 8.4 222 Drift to L, L stifle buckles, spasms into L lumbars, Improved over time.	Could the strong adduction of the LH be part of the excessive stride length of the RH. Work to increase weight bear on LH could help with stabilization.	
90 Days 10/1-12/31							
	Standing exam: Medial sus branches thick and mildly sore. Trot in hand: Ok Under tack: Ok. LH is a bit the weaker corner but ok Plan: Continue working, continue building steadily Back good. Hoof testers negative.	October 22, No treatment December 13 Inj hocks Inj both fore fetlock joints	Si/Gluts	6/mo	8.6 333 Some destabilization of left stifle. But overall balanced, steady, comfortable rotation.	Some inconsistency in quality of rotation, but steady improvements over time.	Add pirouette thoughts to turn where hindquarters remain more stable and forehand lightens more. Keep neck stabilized but stretching up and out. Shoulders can "open" more to better support base of neck. Work includes leg yield and half-pass type exercises.
			Thorax	6/mo	8.2 444 Smooth dorsal/ventral mvmt.	Consistent quality mvmt in this region.	
	December 13, 2018 Has felt restricted behind. Standing exam: Churchill spavin test + both hocks points + Hoof testers negative Tight through shoulders ++ Trot in hand: Very short in front and bilateral, short behind. Longe: RF lame to the left. Flexions: Both hocks +. R shoulder caudal flexion ++. Others ok. Diagnostic block RF abaxial sesamoids: negative Diagnostic block RF low volar: positive, still slow cranial phase of the stride RF to the left but lameness has improved. Assessment: Hocks sore - Most relevant RF fetlock and both shoulder joints active right more than left.	Inj both shoulder joints.	Neck	4/mo	6.0 111 Short triangle Only contracting on R side. Increased discomfort, no mvmt.	Hypertonicity has returned to base of neck. Lost improvement in traction and functional arching during tx.	
			Shoulders	3/mo	R 6.2 121 Strong adduction, tense, curling body to right during contractions L 6.4 222 Better balanced but still hypertonic.	Waited too long to work in this region.	
			Hindquarters	4/mo	R 8.8 222 Better balanced adduction/abduction, less hypertonic in stifle region. L 9.0 222 Relaxed steady contractions Overall much more symmetrical between R and L lateral thighs.	Consistent improvement in the balance of adductor/abductor muscling.	

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Table 3 (*continued*)

Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
120 Days 1/1-5/31	4/28 Has been showing 1.30 doing well!! Standing exam: Low-grade activity stifle points and low-grade synovitis both stifles, medial femoral tibial joints. Medial sus branches organizing - smaller with more firm edges. Back is really strong. Does not resent passive flexion hind fetlocks nearly as much as in the past. L hip area below gluteals there is tearing of the muscle fasica. No pain but irregular feeling of the muscle here (gluteals). Trot in hand: good! Flexions: subtle response from stifle flexions (esp. on circle). All others negative except distal limb LH not flexed in a typical manner. Front end good! Assessment: Generally very good. Low grade stifle joint synovitis - stay ahead of this to avoid overload hind fetlocks.	Inj both stifles medial & lateral femoral tibial joints.	Si/Gluts	5/mo	7.8 333 Now dropping R stifle during rotation…some lateral twist to L during rotation. Some destabilization of left stifle.	Some loss in symmetry and range of motion. However, quick improvements in response to txs.	Stride is much more even, only a few uneven strides in beginning at trot. Canter much better balanced and strides, very even. Position hips to inside on turns. Keep stretching neck up and out not down and out. Neck should remain steady through all transitions (add more walk/canter), and should not lower forehand, especially during the moment of transition. Lengthen and shorten stride with no change in neck position to improve range of motion of spine. Great improvements in overall strength and straightness. 4/20 successfully competed at 1.30 m, clear at international competition.
			Thorax	4/mo	7.8 444 Smooth, consistent	Consistent improvement.	
			Neck	3/mo	6.8 111 Short triangle Inconsistent improvement. Some good traction and arching but tense at beginning of tx.		
			Shoulders	4/mo	R 7.6 222 Still stronger adduction than L L 8.0 323 fairly well balanced with stronger contractions.	Overall improvement in both shoulder's muscle function but still asymmetrical. Could strong R shoulder adduction be tied to RF concern?	
			Hindquarters	3/mo	R 7.4 222 Sustained improvements L 7.8 222 Improved quality of mvmt with lower voltage.	Improved symmetry between mvmt of R and L lateral thighs. Consistent, slow improvements.	

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Table 3 (*continued*)

Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
30 Days6/1-6/30	6/5 Check before showing next week. Standing exam: Right lower neck focally sore over c67. Front fetlock joint synovitis low grade, both. Hoof testers negative. Stifles feel better than last exam. Hocks slight. Hind med sus branches stable, resents hind fetlock flexion. R shoulder joint points +. Trot in hand: Short behind but ok. RF lame 2/5. Slow cranial phase and leaning away from RF limb (slow to bring limb forward like shoulder or neck pain). Flexions: RF distal limb or RF fetlock isolation both ++. Others ok Longe: RF lame 2+/5 to the L. Worse after standing, better with exercise. Worse after shoulder caudal flexion. Diagnostic block RF: Palmar digital nerve block (heels): negative Abaxial (foot): negative block but some improvement, RF fetlock flexion remains ++. Low volar: negative block high volar (sus origin): negative block US exam cervical spine: Remodeling c67, c7t1 both sides, no acute active synovitis. Assessment: Acute RF lameness not originating from sus origin down although fetlock joint active. May be some recent trauma and may resolve quickly. Lower neck / subscapular / shoulder region seems to be the source of lameness, based on physical exam, blocking, and nature of her gait (slow cranial phase going left and worse after standing). plan: walk under tack. review on Saturday after Bute 1 gram Wed and Thur and Fri nights Review at recheck: Lower neck, subscapular, R shoulder joint and both fore fetlock joints. 6/8 Follow up exam in hand and under tack has been on Bute 1 gram once daily Trot in hand: Still lame RF Under tack: RF lame more apparent to the right and RH lame to the right Flexions: RF distal limb +. R shoulder +. RH fetlock a few steps positive then recovers. Dynamic si test improves her gait. Assessment: Monitor RH Treat neck along with R shoulder and front fetlocks first, assess response if RH still needs support then follow through with that.		Si/Gluts	4/mo	9.6 555 Consistently symmetrical rotation with good range of motion.	Surprisingly consistent. Improvement is currently sustained.	Horse has not felt stronger enough to handle increased workload necessary for higher jumps. Uneven in hind limb swing is still a concern. Neck is tight and short at base. Shoulders have improved in symmetry and overall strength. 6/15 Decision to retire horse.

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Table 3 (*continued*)

Case study 3 12-mo Protocol	Veterinary Exam	Veterinary Intervention	FES Tx Region	Number of Tx During Time Frame	Average Voltage and Conductivity Values and Response to Stimulus	Improvements Observed With FES Treatments	Biomechanical Assessment and Mvmt Exercises During Riding
			Thorax	3/mo	8.8 545 Steady dorsal/ventral mvmt, but some counter-clockwise twist returning.	Some hypertonicity but quickly resolved.	
			Neck	2/mo	7.2 222 Short triangle Still tense, short and jammed especially L base of neck, but improved during tx.	Bracing in neck, improvements over tx period but not retained.	
			Shoulders	2/mo	R 7.2 222 Better balanced adduction/abduction L 7.6 222 very good mvmt, relaxed Overall very good improvement, but inconsistent.	Very good changes in symmetry and strength. Mild inconsistences but overall results are sustained.	
			Hindquarters	2/mo	R 8.4 333 Some tension in stifle region L 8.6 323 Maintained previous improvements in symmetry.	Improvements are becoming sustained over time. Pleased with progress but somewhat inconsistent.	

Abbreviations: FES, Functional Electrical Stimulation; Inj, Injections; L, Left; LF, Left front; LH, Left hind; Mvmt, Movement; R, Right; RF, Right front; RH, Right hind; SDF, Superficial digital flexor; SI, Sacroiliac; Sus, Suspensory; Tx, Treatment; US, Ultrasound.

caudal) when compared to the right hind swing phase. During the FES stimulus to the thigh muscles, the right patella showed a medial positioning, or "roll", which is biomechanically incorrect for that joint. It has been observed that this inward roll of the patella during movement produces a longer stride on that limb so all the biomechanical information seemed to correlate. During the FES stimulus of the right lateral thigh region, the mare was noticeably uncomfortable however the abduction/adduction muscular activity was reasonably balanced. In contrast, the left patellar region muscling was hypertense, but when the thigh muscles were activated by FES, a correct lateral "roll" movement of the patella was observed. Improvement in the patellar biomechanics occurred after an intense FES protocol to the lateral thighs and gluteal muscles over a 3-month period. No FES treatments to the shoulder region were performed since the palpation and movement evaluations did not indicate any serious dysfunction.

Specific exercises under saddle which allowed no, to very limited, lateral bending and encouraged equal flexion of the entire hind limb was instituted. Because the left hind displayed a shortened swing phase when compared to the right hind swing phase, the right hind stride length was shortened to match the length of the left hind. This is a technique that has been used successfully in human rehabilitation and appeared to improve the mare's gait in this situation as well. In addition, the medial roll of the right patella was reduced and became more correctly laterally positioned during the swing phase when the mare shortened the length of the stride of the right hind. Once the strides were even in length, then both limbs were asked by the rider to equally increase in stride length over a period of time to eventually obtain a symmetrical stride length of both hind limbs. During this period of stride lengthening, the correct length of stride was determined based on lengthening the stride until the point when the stride length became uneven. Then this specific stride length was the longest stride the mare could correctly perform during that phase of the rehabilitation protocol. She consistently improved the symmetry and length of stride until visually the stride length appeared normal and was evaluated as her "normal" preinjury stride length by the rider.

Veterinary intervention over the next 3 months (July 1–September 30) included periodic shockwave to both hind suspensory ligaments and laser treatment on all four suspensory ligaments. FES treatments were performed on the pelvic region, thorax, neck and hindquarters. All regions but the hindquarters continued to show steady improvements in symmetry and range of motion. The medial roll of the right patella was diminished, and the adductor/abductor muscle activity of the right and left hindquarters was better balanced. However, the left hindquarter region remained hypertonic and stimulus to this area produced left lumbar muscle spasms.

Exercises under saddle continued to focus on maintaining an even length of stride of both hind limbs. During riding, the mare would sometimes exhibit a mild counterclockwise rotation of the thorax which would position her "belly" to the right. In addition, this counterclockwise rotation of the thorax positioned the right patella medially which was biomechanically not ideal and therefore increased the importance of reducing the thoracic twist. The specific correction to straighten the thorax required the rider to position the haunches to the left which was counter to what would be a traditional correction of moving the thorax to the left. It was also determined that when the rider corrected this thoracic asymmetry the mare was able to better accept weight on the left hind. This nontraditional correction was probably due to the medial positioning of the right stifle. It took several changes in positioning during riding to determine this unusual correction and was a good example of how it is important to select the exercise that works rather than the exercise that is the most common fix for a specific problem. Overall, the mare was improving and gaining better balance and strength, and jumping exercises were now added to her training.

During the next 3 months (October 1–December 31) there was some reversal of the progress early in this time period. Veterinary interventions included injections to the hocks, both fore fetlock joints, and both shoulder joints. The FES work found some destabilization of the right stifle had returned but this resolved quickly after the veterinary work. As the time period progressed the right hind limb was much better positioned with the patella appearing to remain correctly laterally positioned during pelvic rotation. Also, the neck became more hypertonic, which was not easily resolved, and improved slowly during the 3-month period. Interestingly, the hindquarters retained the improvements in symmetry and the stride length asymmetry was further reduced, especially by the end of this time period. The most significant negative change occurred in the hypertonicity of the shoulders. The right shoulder showed strong adduction in response to the FES stimulus and the mare would curl to the right during activation of the right shoulder musculature. The left shoulder was not as reactive and showed a more symmetrical adduction/abduction movement. In retrospect, the treatment to the shoulders should have been performed much earlier in the protocol to identify this asymmetry earlier. Exercises under saddle included more hind limb weight-bearing exercises such as pirouette type turns and leg yield and half-pass work to "open" the shoulders. The mare was happy and enjoying the work under saddle, especially the jumping

Over the next 4 months (January 1–May 31) there were overall steady improvements and veterinary interventions included injection of both medial and lateral femoral tibial joints. The pelvic region continued to respond well to the FES treatments and showed improved range of motion and symmetry which was observed in the evenness of the strides of the hind limbs. The thorax continued to show correct functional movement during FES and the hindquarters also showed steady improvement in symmetry, however, there was periodic right stifle destabilizations during pelvic rotation. The shoulder symmetry and quality of movement slowly improved but the right shoulder adduction was still a concern due to the potential of this asymmetrical adduction to affect the movement of the right fore as well as potentially increase the asymmetry in the muscles at the base of the neck.

Riding exercises continued to increase in difficulty with the addition of higher jumps. Lengthening and shortening of the strides were specifically added to assist in keeping the forehand light as the stride length increased. The focus on maintaining an even length of stride of the hind limbs was still primary. Seven months into the protocol the mare competed successfully in several high-level jumping events (up to 1.30 m) and was progressing well.

Eleven months into the protocol the mare displayed a right front lameness, followed by a right hind lameness, with associated neck pain and shoulder pain which did not resolve. Several FES treatments to the pelvic region, thorax, and hindquarters showed continued steady improvements in symmetry and range of motion over time. The shoulders improved the most in symmetry and overall strength between the two shoulders although there was still inconsistent improvement. The neck displayed the highest degree of hypertonicity and muscular dysfunction during this period of time, especially at the base of the left neck. Exercises under saddle still focused on obtaining equal length of stride of both hind limbs as well as encouraging the mare to stretch her neck up and out. Approximately 1 year after FES therapy began, she retired after the chronic right front and right hind lameness.

In summary, utilizing the FES as a diagnostic tool showed that initially, the main musculoskeletal dysfunction in this mare was in the stifle region, predominately in the right stifle. This case was highly unusual because the spinal musculature was basically

symmetrical, and the spinal vertebral movement appeared to be functioning normally. The high degree of biomechanically incorrect movement was isolated to the stifle and gluteal region on the right side which was assumed to produce the strong asymmetrical stride length seen in this mare. When the mare could not correctly accept weight onto her hind limbs, then the forces on the forehand increased producing hypertonicity in the neck and shoulder regions. The lack of success in returning her to competition could be associated with the pathological rotation of the right stifle in response to pelvic rotation, therefore the joint could not accept the forces necessary for high-level jumping. In the authors' opinion when chronic lameness is associated with a single, strong incorrect biomechanical movement pattern, these horses have a lower success rate than when there are several compensatory reactions throughout different regions of the body. Perhaps "spreading out" the incorrect biomechanics helps to reduce the degree of pathological forces to a single area, therefore reducing the chance of reinjury

All three case studies show that, with the combined use of current veterinary diagnostic and treatment options used together with FES, it may be possible to improve the rehabilitation timeline and outcome for horses. FES can offer diagnostic information about the functional movement, symmetry, and range of motion of the musculoskeletal system which may prove useful in the advancement of diagnostics and treatment in veterinary medicine.

5. Conclusions

When the biomechanics of physical movement is not correct, compensations occur in an attempt to rebalance the dysfunction. As a result of these compensations, the biomechanics of the body becomes inefficient, and then typically, over time, these alterations produce pain and dysfunction of the neuromuscular system and breakdown of the musculoskeletal system [71]. Late-stage structural faults of the body usually begin as alignment faults and pain does not generally occur until the alignment fault becomes severe [72]. Unfortunately, just removing the pain will not automatically solve the problem, and result in optimal healing, if the incorrect mechanics are not addressed. In contrast, primary pain such as from trauma may cause the biomechanics of the physical movement to change as a reaction to the injury [73]. However, no matter why or how the biomechanics of the musculoskeletal system becomes pathological, improving the biomechanics of the body is essential to successful rehabilitation.

With FES technology, muscle movement can be created and evaluated in a controlled environment which helps to improve kinematic observations. The stimulation produced by FES creates musculoskeletal movement that is essentially identical to voluntary movement [39]. The careful observation of the associations between different regional movement patterns created by FES has aided in the development of treatment protocols in veterinary medicine and the potential exists for the transfer of this diagnostic technique into human medicine.

Clinically, the authors have found that the evaluation of the muscle movement produced by FES has helped to resolve some complex lameness issues by assisting in the focus of the location and sequencing of treatment options. Because pain can be multifocal and not always associated with the site of the pathology [70], the regional movement created by FES can provide data that can add information to traditional diagnostic options. Since research in horses has shown that positive changes in musculoskeletal function and symmetry are a result of FES [43–47] and that FES mimics voluntary muscle movement [6–10], the development of the use of FES as an additional safe and effective diagnostic option seems reasonable.

Case studies in this paper illustrate how FES was incorporated into traditional diagnostic and treatment protocols in veterinary medicine and clinical cases showing how this technology can be adapted from human medicine. In addition, the case studies specifically discuss when and how to utilize the kinematic information the FES technology provides. Regionally isolating musculoskeletal immobility and pathological movement, through the use of FES, has been able to add dynamic diagnostic information to existing diagnostic options in veterinary medicine helping to improve treatment and rehabilitation protocols.

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Supplementary materials

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