Journal of Equine Veterinary Science 91 (2020) 103116

Contents lists available at ScienceDirect

Journal of Equine Veterinary Science

journal homepage: www.j-evs.com

Original Research

Movement Caused by Electrical Stimulation of the Lumbosacral Region in Standing Horses

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ARTICLE INFO

Article history:
Received 15 January 2020
Received in revised form
12 April 2020
Accepted 4 May 2020
Available online 13 May 2020

Keywords:
Electrical stimulation
Lumbosacral
Sacroiliac
Physical therapy
Pelvic inclination

ABSTRACT

Electrical stimulation is commonly used as a modality for physical therapy in human and veterinary medicine. However, studies measuring the movement generated by electrical stimulation in horses are rare. The present study therefore evaluates the range of movement provoked by a commercially available physical therapy unit (FES310) and contrasts it with the movement generated by manually induced pelvic inclination (back rounding). Ten horses were tested on three measurement days over one week. Electrical stimulation was applied via a back treatment pad (belonging to the FES310 system) containing six electrodes (three on either side of the spine) placed over the lumbosacral region. This system produced a pulsed, biphasic electrical stimulation in a rectangular waveform which was gradually increased to a maximum of 10 volts. Before and after electrical stimulation testing, manual pelvic inclination was achieved by pressure on two points lateral to the root of the tail. Muscle tone and lameness were evaluated before and after treatments. Skinfold thickness, body condition score, and body mass were measured to detect possible confounding factors. Using kinematics, the angle ranges during movement of ten three-dimensional angles of the trunk, the pelvis, and the hind limbs were further analyzed. Movement was produced with manual stimulation in every tested individual on all measurement days and with electrical stimulation on at least one measurement day. The electrical stimulation led to significantly ($P < .05$) smaller angle ranges which were 15 %–57 % of the median of the manually stimulated movement. Strong positive correlations between angle ranges of the electrically generated movement were found for the hind limbs implicating their involvement in the movement created. Correlations between skinfold thickness, body condition score, and body mass with the angle ranges were weak and not significant. Before and after electrical and manual stimulation, muscle tone and lameness were similar. In the present study, both electrical and manual stimulation were proven to produce significant trunk and hind limb movement. Within this study's electrical stimulation treatment protocol, the movement generated by electrical stimulation was significantly less than the movement caused by manual pelvic inclination. However, electrical stimulation could easily be applied over a longer period and in a higher frequency than it would be possible for manual pelvic inclination. This treatment shows potential for stabilization and or mobilization of the lumbosacral region, although its efficiency as a therapeutic tool and its effect on specific orthopedic problems and is to be evaluated in further research.

1. Introduction

Studies regarding the topic of electrical stimulation (ES) have been using contradictory terminology, with terms such as functional ES, neuromuscular ES, and transcutaneous ES being used inconsistently [1,2]. The name of the commercially available electrotherapy unit used in the present study (FES310, EquiNew LLC, River Falls, WI) includes the term functional electrical stimulation (FES). In an attempt to clarify the naming of the different submodalities of ES,

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Animal welfare/ethical statement: Discussed and approved by the institutional ethics and animal welfare committee in accordance with GSP guidelines and national legislation.

Conflict of interest statement: The authors declare no conflicts of interest.

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https://doi.org/10.1016/j.jevs.2020.103116
0737-0806/

Doucet et al. pointed out that FES usually refers to the process of pairing the stimulation simultaneously or intermittently with a functional task [1]. As this is not the case in the present study, it may be more fitting to the general term neuromuscular electrical stimulation (NMES), which describes a repeated application of current to produce contraction of innervated muscle by depolarizing local motor nerves [2]. Because of these differences in nomenclature, the basic term ES is used in the remainder of this article.

In veterinary medicine, and specifically in equine medicine, studies evaluating the movement generated by ES in its various forms of use are rare, despite a wide variety of applications already in use in dogs, cats, and horses [3–9]. Therefore, the present study sets out to document the effects of a commercially available electrostimulation unit applied to the lumbosacral region of the horse.

The topic of the present article is restricted to the transcutaneous application of electricity to achieve muscle contractions. Such an application of electricity as a very old therapeutic modality is based on the observation of Luigi Galvani in 1790 that applying electrical current to leg muscles severed from the body of frogs creates appreciable movement [10]. Later, in 1831, Michael Faraday invented the first transformer with which the first treatments were made possible [10]. Today, ES is frequently used for rehabilitation of neurological and orthopedic conditions in human medicine, such as foot drop syndrome [11,12], spinal cord injury [13,14], total hip replacement [15], total knee arthroplasty [16–18], anterior cruciate ligament rupture [19,20], and arthritis [21,22].

In small animal veterinary medicine, electrotherapy is established for conditions such as cranial cruciate ligament rupture in dogs [7–9], and it has been used clinically in dogs to diminish joint contractures and to decrease muscle atrophy (associated with postoperative atrophy, nerve injury and inherited Labrador myopathy), as well as to decrease pain, muscle spasm (associated with intervertebral disk disease), and edema [23]. Electrotherapy is even used for cats with osteoarthritis or spondylarthrosis [6]. In equine medicine, ES can be used for headshaking [24,25], to help with problems of the laryngeal nerve [26–28], and to reduce epaxial muscle spasms and hypertonicity [4,5,29]. In addition, NMES is a useful adjunct to assess and treat muscle dysfunction and/or atrophy in cases such as suprascapular and radial nerve lesions [30].

In human physical therapy, benefits and effects of topically applied ES have been documented in detail. They include, for example, preservation of muscle mass [31] and improvement in muscle strength [32]. It is also a very efficient modality for reducing upper and lower limb edema [33]. Electrical stimulation is especially indicated during bed rest [34], or in patients who have limited training options due to, for example, respiratory conditions such as COPD [35]. Owing to some of those benefits, more recent studies even suggest the use of ES in spaceflight [36] as the muscles of astronauts are not adequately challenged in the absence of gravity. However, a recent review lists several studies that did not show significant differences of ES therapy compared with voluntary training regimes in humans [37], where voluntary movement is more readily achievable than in equine patients.

Despite the documented beneficial effects, there are a few limitations that should be considered. The movement produced by ES is described to be inherently less efficient than voluntary movement [1], even though this efficiency is not further characterized. Depending on stimulation intensity and duration, ES is also described to induce neuromuscular fatigue [1]. This exertion of muscle is also shown by Jubeau et al. who documented that muscle contractions induced by ES resulted in greater increases of blood lactate concentration, serum creatine kinase activity, and muscle soreness, but also growth hormone release [38].

Contraindications for use of ES include high-intensity stimulation in patients with pacemakers and/or seizure disorders [23]. Furthermore, ES should not be used directly over the heart, over areas of thrombosis or thrombophlebitis, infected areas or neoplasms, areas of impaired sensation, skin irritation, or skin damage [23]. It should also not be performed over the trunk during pregnancy and over the carotid sinus [23]. Finally, ES that generates movement should not be used any time active motion is contraindicated [23]. Usage over or through the thoracic cavity and in patients with fevers or infection is also not recommended [3].

The purpose of the present study was to evaluate the movement that can be achieved with dorsal lumbosacral ES in horses. Therapeutic effects of muscle stabilization and mobilization for this region are of high interest because back pain is a common health problem in the equine population; it can cause chronic pain, limit performance, and impair ability to work, which constitutes a common concern for veterinarians [39]. The lumbosacral and pelvic region transfers the motion of the hindquarters up through the back and forward to the forehand [40] and kinematic studies suggest that even subtle hind limb lameness can alter movement of the thoracolumbar region, potentially contributing to secondary musculoskeletal pain in the region [41]. Zaneb et al. stated that chronic lameness in horses induces important changes in function and use of muscle groups such as longissimus, semitendinosus, and gluteus muscles, and that these lameness-related changes contribute to the increased incidence of muscle pain in lame horses [42]. Lumbosacral or sacroiliac soreness, as well as delayed patella release problems, may cause a decrease in performance without specific lameness being observed [43,44].

The present study aimed to document the movement that can be generated by ES of the lumbosacral region in horses. In addition, the movement created by ES is compared with the movement of back rounding (syn. pelvic inclination) achieved by manual stimulation.

2. Materials and Methods

This study was discussed and approved by the institutional ethics and animal welfare committee in accordance with GSP guidelines and national legislation.

2.1. Horses

For the purpose of this study, 10 horses (5–20 years; 5 geldings, 5 mares; 6 Standardbreds, 1 Haflinger, and 3 Warmbloods; body mass 485–682 kg) from the university teaching herd were selected. The horses were kept on a paddock in a group; they did not undergo a specific training regime beyond trotting up and occasional lunging for teaching.

2.2. Exclusion/Inclusion

All horses underwent a clinical examination focusing on the back and the pelvis as well as lameness evaluation. Horses were excluded from the study if they showed asymmetries of the pelvic or gluteal areas or overt pain on back or pelvis examination. Furthermore, horses were evaluated for lameness—supporting limb lameness of more than 1/5 (graded from 0 to 5) or more than mild swing phase lameness (graded as mild to severe) led to exclusion from this study.

2.3. Data Collection

The study was scheduled as follows: Data were collected on three days within one week, with a break of one or two days between measurements; further referred to as measurement day 1 (MD1), measurement day 2 (MD2), and measurement day 3 (MD3).

On each MD, all horses were again evaluated at walk and at trot in hand on a hard surface in a straight line before, immediately after, and 30 minutes after measurements (for definition of lameness grading see section “Exclusion/Inclusion”). In addition, the muscle tone of the longissimus dorsi and gluteal muscles was assessed on each side manually before and after each measurement (classified as not increased or from minimally to severely increased muscle tone). Muscle tone and lameness assessment was carried out by the same clinician (T.F.L.) in all cases; study design did not allow for blinding of these assessments.

For the present study, the commercially available FES 310 (EquiNew LLC., River Falls, WI) and the corresponding preshaped back treatment pad were used. This system has a 16-bit digital microcontroller and provides a biphasic, rectangular waveform at 60 Hz, with a zero net charge. It produces a pulsed signal with a rate of 2 seconds on and 2 seconds off at 2 volts, which continuously increases to 6 seconds on and one second off at 10 volts. The back treatment pad contains six electrodes, three on each side of the midline. Between pairs of electrodes electricity flows in a rectangular shape wave connecting the cranial one on the left with the caudal one on the right, the left and right middle electrodes, and the caudal electrode on the left with the cranial one on the right (Fig. 1). Conductivity values of these electrode pairs are continuously displayed on the control unit, with the maximum conductivity value possible being 9. The electrode position within the pad remained the same for each horse and each MD, resulting in minor differences of the electrode position on the horse, depending on the fit of the preshaped pad.

Before positioning the back treatment pad, the skin was moistened with water; in addition, electrode gel was used between the electrodes and the skin to reduce impedance. The rectangular back treatment pad (43 cm by 58 cm) was taped down over the lumbar and sacral spine, starting on the second or third lumbar vertebrae and reaching to the last third or the end of the sacral bone region depending on the size of the horse with its width reaching the mid gluteal region. The control unit weighing about 2 kg was attached to the left side of a surcingle at mid thoracic level and an additional camera recording its display was attached; on the right side at the same level, a counterbalance of 2 kg was attached. A heart rate monitoring system (S810i TM Polar, Polar Electro, Kempele, Finland) was placed over the thorax directly caudal to the surcingle (Figs. 2 and 3). Another additional camera was connected to the Eagle system, recording each measurement from the side.

Reflective spherical markers were attached to the horse with textile adhesive tape. Horses were walked onto the unmoving treadmill with side bars in the opposite direction of its movement direction, to avoid horses attempting to walk or trot on the treadmill, as they were all accustomed to treadmill locomotion from earlier studies. Ten high-speed cameras (Eagle Digital Real Time System, Motion Analysis Corp., Santa Rosa, CA) were mounted on a ceiling frame around the treadmill. The measurement area was calibrated at the start of each MD using standard procedure; the right-handed Cartesian coordinate system was used. Measurements at a rate of 120 frames per second were taken for 10seconds on MD1 and MD2. However, based on preliminary data analysis of MD1 and MD2, on MD3, measurements of 20seconds were taken to allow for collection of more movement data, as some data were of poor quality because of fidgeting of the horses (see also section “Data Processing”). On MD1, one horse was measured with a marker setup of 18 markers; all other horses on MD1 and all horses on MD2 were measured with 37 markers. On MD3, 41 kinematic markers were placed on most body parts (Fig. 2). In case markers became loose during measurements, those markers were removed for this MD and therefore they were not available for data processing.

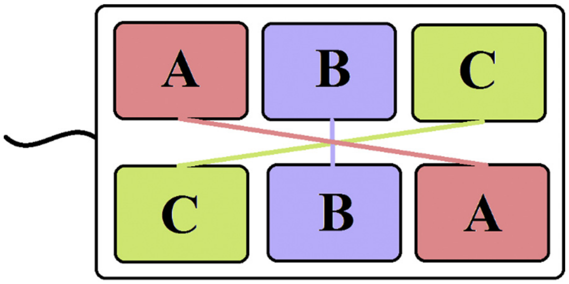

Fig. 1. Electrode placement of the three electrode pairs in the back treatment pad.

One measurement at stance of each horse without ES was taken on each MD. After that, ES was started at a voltage of 2 volts (V); it was then slowly increased to 5 volts with steps of 1 volt. From 5 volts onward, current intensity was only increased after a minimum pause of 1 minute if the horse did not show facial or other signs of discomfort associated with ES and if the heart had not reached more than 48 bpm. If necessary, a longer pause was allowed until signs of discomfort had dissolved and the heart rate had decreased beyond 48 bpm. The increase of voltage was stopped if one of two scenarios was reached: either if marked movement of the lumbosacral region was observed (as determined by three evaluators present at the measurement) or if 10 volts had been reached. This methodology was the prerequisite to obtain approval of the ethics committee. The preset total duration of ES was 20 minutes.

Before and after ES, pelvic inclination was achieved by manual stimulation of two points lateral and slightly cranial to the root of the tail in the groove between semitendinosus and biceps femoris (Figs. 3 and 4). On MD1 and MD2, one manual pelvic inclination (MPI) before and one after ES and on MD3, three MPIs before and three after ES were carried out. MPI was carried out by the same clinician (T.F.L.) in all cases, similar to the routine clinical examination procedure using the amount of pressure necessary to achieve maximum effect; the pressure used varied depending on the individual horses. Furthermore, there was no attempt made to standardize either limb position or posture before MPI as this could not be done for ES measurements.

On MD3—after finishing all measurements—body mass, body condition score (BCS), and skinfold thickness (SFT) were documented. The SFT was measured on the neck using a digital caliper (Electronic Digital Caliper, Powerfix, Lidl Stiftung und Co KG, Neckarsulm, Germany).

2.4. Data Processing

The movement of the kinematic markers was tracked using CORTEX (Version 7.0.0.1802; Motion Analysis Corp., Santa Rosa, CA) and the resulting traces were smoothed using a Butterworth filter at 15 Hz. Of the resulting data, ten three-dimensional angles (Fig. 5) between markers were calculated in CORTEX and used for further analysis. Markers on the back and hind limbs were chosen to calculate these ten angles to optimally display the performed movement.

The parts of the measurements deemed unsuitable for further analysis were either incomplete due to the loss of marker positions or due to an excess of body movement not associated with the stimulated movement. Excessive movement was defined as loss of contact between one of the 4 hoofs and the ground (step, scrambling, shifting weight), eyes lower than side bars, head tilted backward, neighing, shaking, or other sudden movements; these criteria for exclusion were elaborated via randomized evaluation of the video footage taken simultaneously to measurements. Within the measurements used, a minimum of 7 seconds (in accordance with the on/off time of the electrical stimulus at 10 volts) was used for ES and measurements

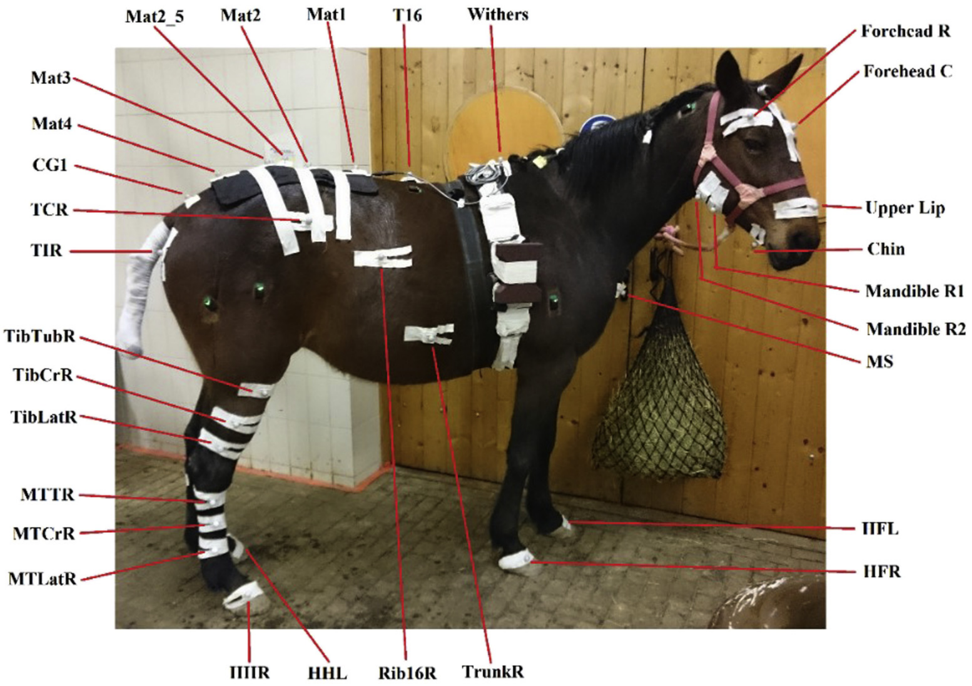

Fig. 2. Position of the equipment and kinematic markers used. Kinematic markers were taped onto the horse, as well as the back treatment pad over sacral region. The surcingle (with a counterbalance to the FES310 control unit—not visible because on left side—at mid thorax level) was placed directly cranial of the belt for heart rate monitoring; Forehead L/mandible L/markers on left side on left hind limb not shown; R = right, L = left C/Cr = cranial, Lat = lateral, F = forelimb, H = hind limb, TC = tuber coxae, TI = tuber ischiadicum, Tib = tibia, Tub = tuberositas, MT = metatarsal, CG1 = root of the tail, Mat1-4 = markers on back treatment pad 1–4, T16 = thoracal vertebra 16, MS = manubrium sterni.

at stance (measurements without ES or MPI), whereas a minimum of 2 seconds was used for measurements of MPI.

The onset of apparent movement achieved by ES was evaluated from video files taken simultaneously to measurements. Conductivity values were noted as maximum conductivity values seen per voltage used per horse and MD from the record of the monitor of the control unit.

2.5. Statistics

For this study, only angle ranges were used for further calculations, except for the comparison of measurements at stance on the three MDs; in this case, angles as such were compared. For comparisons, the Wilcoxon test was used and, in case of more than two compared data sets, corrected according to Bonferroni. Coefficients of determination and Pearson correlation coefficients were calculated in Excel (Microsoft Corporation, Redmond, WA). Owing to the small number of horses measured, all correlation results with an r^2 above 0.4 are presented.

The following three major groups were created to compare the mean values of movement: (1) measurements at stance without ES and measurements with minor ES (group S/MinV), (2) measurements at maximum ES (MaxV), and (3) measurements at MPI before and after ES (MPI).

Fig. 3. Side view of a horse positioned for the measurement between two sidebars. Horse at stance without any stimulation (neither electrical, nor manual).

Fig. 4. Horse at the maximum of manual pelvic inclination (MPI).

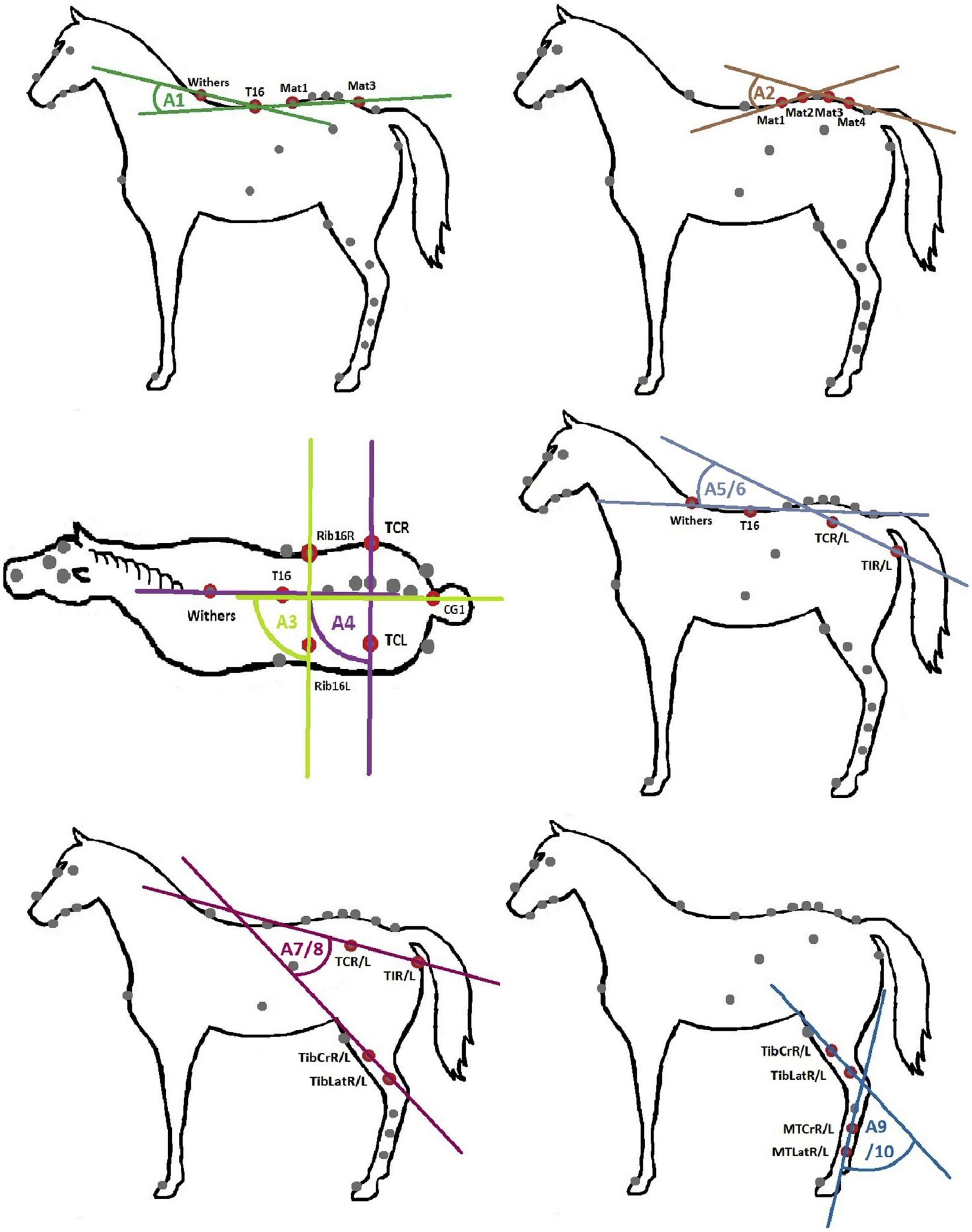

Fig. 5. Schematic presentation of the ten angles and the markers used for calculating each. R = right, L = left C/Cr = cranial, Lat = lateral, TC = tuber coxae, TI = tuber ischiadicum, Tib = tibia, Tub = tuberositas, MT = metatarsal, CG1 = root of the tail, Mat1-4 = markers on back treatment pad 1–4, T16 = thoracal vertebra 16; top left: angle 1 = withers-T16-Mat1-Mat3; top right: angle 2 = Mat1-Mat2-Mat3-Mat4; middle left: angle 3 = T16-CG1-Rib16R-Rib16L and angle 4 = withers-T16-TCR-TCL; middle right: angle 5 = withers-T16-TCR-TIR and angle 6 = withers-T16-TCL-TIL (one on each side); bottom left: angle 7 = TCR-TIR-TibiaCrR-TibiaLatR and angle 8 = TCL-TIL-TibiaCrL-TibiaLatL (one on each side); bottom right: angle 9 = TibiaCrR-TibiaLatR-MTCrR-MTLatR and angle 10 = TibiaCrL-TibiaLatL-MTCrL-MTLatL

3. Results

3.1. Stance and Movement

On all three MDs, all 10 horses were measured, with 2 horses later being excluded on MD2 and MD3 as no conductivity was observed (see supplementary files Table 1). No significant difference in the initial posture of the horses was found comparing the defined average angles in the stance measurements on MD1, MD2, and MD3.

Rhythmical movement caused by ES (see supplementary files video “Electrical stimulation”) was noted in 4 horses on MD1, 6 horses on MD2 and 7 horses on MD3 (Table 1). While on MD1, 75% of horses needed 10 volts to show appreciable movement, it was only 33% on MD2 and 29% on MD3 (Table 1). This is especially interesting because 2 horses were not displaying conductivity values on MD2 and MD3. The voltage necessary to create appreciable movement, however, was not significantly different for the three MDs.

In the cases where voltage was not increased to the maximum of 10 volts neither increased heart rate, nor signs of discomfort were the reason for deciding not to increase the voltage. In these horses, voltage was not increased further because they already showed marked movement at lower voltages and this was a cutoff point based on our ethics submission (see also section “Data Collection”). In two horses (both on MD2), voltage later had to be decreased again because of too intense movement caused by ES. The maximum voltage used for each horse per MD is further referred to as maximum volts (MaxV).

3.2. Conductivity

The conductivity observed never decreased with increasing voltage used—it either remained stable or increased (Table 2). Onset of displayed positive conductivity values varied between 4 and 10 volts. A conductivity value of 4 (of 9) was reached in one measurement at 10 volts in one of the diagonal electrode pairs. Over all measurements of all horses per MD, positive correlations between increasing voltage used and conductivity observed were shown (MD1: pcc = 0.68, n = 90, $r^2 = 0.46$; MD2: pcc = 0.56, n = 68, $r^2 = 0.31$; MD3: pcc = 0.67, n = 67, $r^2 = 0.44$; all MDs: pcc = 0.46, n = 225, $r^2 = 0.41$). In addition, correlations between voltage and conductivity for each individual horse and each MD are presented in Table 3, with H3 being the horse with the most distinct correlation values. No significant differences were noted between the conductivity values observed at 6 volts of each MD, which was the highest voltage used for every horse on all MDs.

3.3. Angle Ranges

Over all horses, there was no correlation between the angle ranges (ARs) for any of the 10 defined angles (see Fig. 5) calculated and either conductivity reached, or voltage applied, neither for the individual MD1, MD2, and MD3 nor for all MDs. Multiple strong correlations between conductivity values, as well as voltage applied, and ARs were found for each horse on each MD. Correlations with r^2 above 0.4 between voltage and ARs were positive in 58 of 65 cases and 74 of 77 cases between conductivity and ARs (see supplementary files Tables 2 and 3). A summary of the occurrence of r^2 values for conductivity and volts with r^2 above 0.4 is shown in Table 4. Many strong positive correlations were also found between individual ARs of ES measurements (see Table 5). However, no such correlations with r^2 above 0.4 were present for the ARs during MPI measurements. Furthermore, the results presented in Table 5 indicate corresponding flexion and extension movements of the joints of the lower limbs by showing strong correlations between the ARs of lower and upper limb ARs.

Table 1
Voltage at onset of visible electrically induced, rhythmical movements for each horse (H1-10) and measurement day (MD1-3), in brackets is the repetition of voltage if it was the maximum voltage used; gray: conductivity of 0 displayed during whole measurement, which led to exclusion of affected measurements from electrical calculations.

Horse	MD1	MD2	MD3
H1	10 (10)	8	8 (1)
H2	10 (3)	4	6
H3	-	-	10 (2)
H4	-	5	10 (1)
H5	-	-	-
H6	-	10 (1)	-
H7	10 (7)	-	7 (1)
H8	-	10 (2)	-
H9	9	-	9
H10	-	5	8

There was no significant difference between ARs of ES measurements at MaxV on MD1, MD2, and MD3. Likewise, there was no significant difference in ARs at 6V on MD1, MD2, and MD3. In addition, there was no significant difference between the ARs of measurements at stance and the first applicable measurements at minor voltage used (measurements used were either at 2 or 3 volts, further referred to as MinV). There was neither a significant difference between the ARs of MPI on either MD before or after measurements, nor a significant difference between the ARs of MPI before and after measurements of all MDs (see supplementary files video “Manual pelvic inclination”). MPI could not be performed on one horse (H10) because of concerns regarding the safety of the examiner. The results showing the significantly different comparison of all ARs of the groups S/MinV, MaxV, and MPI (see also section “Statistics”) are shown in Fig. 6 and Table 6.

3.4. Skinfold Thickness/Body Condition Score/Body Mass

There was a positive correlation between SFT and BCS (pcc = 0.72, n = 10, $r^2 = 0.52$), but there was no correlation with a r^2 above 0.4 between either BCS (ranging from 3.16 to 8.33, median = 5.42), SFT (ranging from 2.55 mm to 5.07 mm, median = 3.39), or body mass (ranging from 485 kg to 682 kg, median = 574.5 kg) and conductivity, voltage used, or ARs reached.

3.5. Lameness and Muscle Tone

Lameness scores before, immediately after, and 30 minutes after measurements did not show any significant differences. Furthermore, the muscle tone of the long back and gluteal muscles did not show any difference before and after treatments.

4. Discussion

The methodology used in the present study was adapted from Licka et al. for the technique of MPI [45], from De Keyser et al. for the measurement of the SFT [46], from Dugdale et al. for BCS assessment [47], and from the FES 310 user manual [48].

The present study documented the movement created by ES of the lumbosacral region in standing horses without known pathologies of the trunk and limbs. To the author’s knowledge, this is the first study documenting this effect in horses even though such documentation is a prerequisite for the evidence base of equine physical therapy. It should be noted that different effects may be created in horses with indications for this type of treatment, such as loose patella syndrome or sacroiliac pain [49].

The greatest amount of dorsoventral movement of the thoracolumbosacral spine takes place at the lumbosacral junction [50,51]. The muscles of the spine and pelvis are major contributors to the stability of the sacroiliac region. On the dorsal aspect, the middle gluteal and superficial gluteal muscles and their fasciae support the sacroiliac region [52]. As the back treatment pad was placed over this region, the stimulation may train local muscles and thus help in stabilizing the sacroiliac region, while also creating marked movement potentially increasing mobility. Whether this treatment modality has more of a mobilizing or of a stabilizing

Table 2

Displayed conductivity values (sum of electrode pairs A, B, and C) at voltage (V) used for each of horse (H1-10) per measurement day (MD1-3); yellow: positive values (lighter yellow if voltage was later decreased), lighter gray: voltage was not used in this horse on this day; darker gray: no conductivity values above 0 displayed at any time of this measurement day for this horse—these horses were excluded from electrical calculation.

MD	Horse	2V	3V	4V	5V	6V	7V	8V	9V	10V
MD1	H1	0	0	0	0	0	0	2	2	5
	H2	0	0	0	0	0	0	0	0	3
	H3	0	0	1	1	4	4	7	9	10
	H4	0	0	0	1	2	4	5	6	8
	H5	0	0	0	1	1	3	4	5	5
	H6	0	0	0	0	0	0	1	1	2
	H7	0	0	0	0	0	0	0	0	2
	H8	0	0	0	1	1	3	3	4	6
	H9	0	0	0	0	1	2	2	4	5
	H10	0	0	0	1	1	1	2	2	3
MD2	H1	0	0	0	0	0	1	2	3	5
	H2	0	0	0	2	4				
	H3	0	0	1	2	3	6	7	8	
	H4	0	0	2	3	4	6	7	9	
	H5	0	0	0	0	0	1	2	2	4
	H6	0	0	0	0	0	0	1	3	4
	H7	0	0	0	0	0	0	0	0	0
	H8	0	0	0	0	0	0	0	0	0
	H9	0	0	0	0	0	0	0	0	1
	H10	0	0	0	0	0	0	0	2	2
MD3	H1	0	0	0	1	3	3	6		
	H2	0	0	0	0	0	2	3		
	H3	0	0	0	1	3	4	6	7	9
	H4	0	0	0	0	0	0	0	1	1
	H5	0	0	0	1	1	2	3	5	6
	H6	0	0	0	0	0	0	0	0	0
	H7	0	0	0	0	0	1			
	H8	0	0	0	0	0	0	0	0	0
	H9	0	0	0	0	0	0	1	2	2
	H10	0	0	0	0	0	0	2	2	

effect for the lumbosacral and sacroiliac region cannot be concluded from our data. It is most likely a combination of both depending on the voltage used, duration, and frequency of said treatments—this needs to be evaluated in future studies. Because of the correlations between the movement of the lower back and even the hind limbs shown in this study, an additional training effect of the muscles of the upper and lower hind limb might as well be possible.

The electrically generated movement was compared with movement achieved by manual stimulation of two points besides the root of the tail, which is a common way to assess problems in this area [53,54]. Examination of the mobility of the spine can give specific information about reduced range of motion in the sacroiliac and lumbosacral region [52]. Of course, the MPI resulted in much larger movement than the movement induced by ES. The MPI was performed to achieve maximum range of motion, whereas ES was used until marked movement was achieved with standard treatment protocols. A different ES treatment protocol with higher voltages applied might have produced higher ARs for ES and therefore less significant differences between ES and MPI.

MPI resulted in weak, nonsignificant correlations between any of the ARs of the ten angles analyzed. This could be due to the smaller number of measurements of manual stimulation that were available for these calculations. By contrast, moderate to strong but also not significant correlations between ARs were found with ES. From the correlation pattern of the ARs, a distinct group of angles including the pelvic inclination (AR6, AR5—see Table 5) and its rotation in the horizontal plane (AR4—see Table 5) was found; this

Table 3

Correlations between conductivity and voltage used for each horse (H1-10) and for each measurement day (MD1-3), as well as for measurement day 1, 2, and 3 (MD1+MD2+MD3) in total; numbers = coefficient of determination (r2); red shades mark the level of Pearson correlation coefficient (PCC), white = r2 under 0.4, gray = nonadmissible (n.a.) because of 0 conductivity or lack of data.

MD	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
MD1+MD2+MD3	0.60		0.93	0.41	0.78				0.41	0.62
MD1	0.63		0.93	0.89	0.91	0.67		0.93	0.85	0.91
MD2	0.76	0.80	0.95	0.98	0.76	0.64				0.53
MD3	0.84	0.72	0.94	0.53	0.88		0.43		0.69	0.57

PCC	
0.90-1.00	🟥
0.75-0.90	🟥
0.63-0.75	🟥
n.a.	⬜

Table 4
Number of correlations with a coefficient of determination above 0.4 per angle range (A1-10) for either conductivity or volts; red shades mark the incidence with darker red indicating a higher incidence and lighter red indicating a lower incidence; n = number of measurements applicable.

Number	AR1	AR2	AR3	AR4	AR5	AR6	AR7	AR8	AR9	AR10
	W-T16-Mat1-Mat3	Mat1-Mat2-Mat3-Mat4	T16-CG1-Rib16R-Rib16L	W-T16-TCR-TCL	W-T16-TCR-TIR	W-T16-TCL-TIL	TCR-TIR-TibCrR-TibLatR	TCL-TIL-TibCrL-TibLatL	TibCrR-TibLatR-MTCrR-MTLatR	TibCrL-TibLatL-MTCrL-MTLatL
n	23	22	21	22	22	22	21	22	21	21
n r^2 Cond > 0.4	8	13	7	9	9	8	8	10	2	3
n r^2 Volt > 0.4	6	14	7	7	5	8	5	10	2	1

may indicate their close relationship. These results show that the electrically produced movement is not only a flexion-extension movement of the trunk, but also may be able to provoke other types of movement such as lateral bending. Some horses seemed to move more to the sides than others, with one horse (H2) even leaning against the side bars on alternating sides during ES (supplementary files video "Leaning against side bars") but showing no lateral leaning during MPI. Why horses reacted with different movement patterns to similar stimulation of the six electrodes is to be evaluated in further studies. One reason may be the difference in contact of certain electrodes and therefore unevenly distributed ES. Further research should evaluate the application of electricity through which electrode pair produces which kind of movement. On the other hand, some of the horses repeated their specific type of movement on more than one day. For example, H2 showed the aforementioned lateral leaning movement pattern with ES on all three MDs. Setup problems are unlikely to have caused consistent lateral movement of this horse on all three MDs and therefore other reasons for this kind of movement have to be considered. Another possible explanation is that pain or pathoanatomical variations (such as contractures of ligaments) might lead to the inability to create a flexion-extension movement and therefore was compensated by that is lateral leaning. It is known that reflexes that induce dorsal and ventral flexion can be suppressed due to pain in the sacroiliac region [52]. No evidence of this kind of pain was found in the initial clinical examination (see section "Exclusion/Inclusion"), and therefore, no such horses were knowingly measured; it follows that this might not be the reason for the movement observed in this case.

In seated humans, the effects of the stimulated quadriceps muscle are localized to the trained thigh muscles and do not extend to the proximal trunk muscles [55]. This is different in standing horses, where to allow the kind of movement shown in the present study horses need to contract additional limb and trunk muscles to remain standing and therefore these muscles also undergo some training. The close correlations of the ipsilateral limb ARs of AR7/AR9 and AR8/AR10 (for clarification see Fig. 5) are most likely explained by the functional reciprocal apparatus [56]. Although the effect of MPI is much larger than the effect of ES, it cannot practically be repeated as many times as ES. Ten minutes of ES at 10 V result in 85 movement cycles—this frequency of impulses is not achievable with MPI. Therefore, ES may well be a more useful training aid and rehabilitation for iliosacral and stifle problems as the manual stimulation. The ES protocol used in the present study caused a significantly smaller movement range than MPI and is therefore more likely to have a mobilizing and/or stabilizing training effect. On the contrary, MPI has been described to have a stretching effect with recommendations for optimal passive stretching in the horse include applying 4 to 5 repetitions of slow, low-load forces held at the end range of motion of the affected tissues, with each stretch applied and released in 30-second cycles [50].

The present study was restricted to a relatively short period (maximum 7 days); therefore the absence of statistically significant differences between MD1 and MD3 cannot directly be attributed to a lack of training effect. Also, no differences between the ARs of MPI before and after ES were found. Therefore, we could not show that ES leads to fatigue of the muscles responsible for pelvic inclination.

Table 5
Correlation between angle ranges (A1-10); red shades marking the level of PCC, white = r2 beyond 0.4, gray = not admissible because of duplicity of data, n = number of measurements applicable.

AR	AR1 W-T16-Mat1-Mat3	AR2 Mat1-Mat2-Mat3-Mat4	AR3 T16-CG1-Rib16R-Rib16L	AR4 W-T16-TCR-TCL	AR5 W-T16-TCR-TIR	AR6 W-T16-TCL-TIL	AR7 TCR-TIR-TibCrR-TibLatR	AR8 TCL-TIL-TibCrL-TibLatL	AR9 TibCrR-TibLatR-MTCrR-MTLatR	AR10 TibCrL-TibLatL-MTCrL-MTLatL
AR1 (n=24)			0.56	0.52	0.57	0.52	0.44	0.43		
AR2 (n=23)			0.48	0.54	0.41	0.60				
AR3 (n=23)				0.82	0.79	0.79	0.41	0.41		
AR4 (n=23)					0.90	0.94	0.41			
AR5 (n=23)						0.81				
AR6 (n=23)							0.46			
AR7 (n=23)								0.53	0.62	
AR8 (n=23)										0.72
AR9 (n=23)										
AR10 (n=22)										

PCC	
0.90-1.00	🟥
0.75-0.90	🟥
0.63-0.75	🟥
n.a.	▨

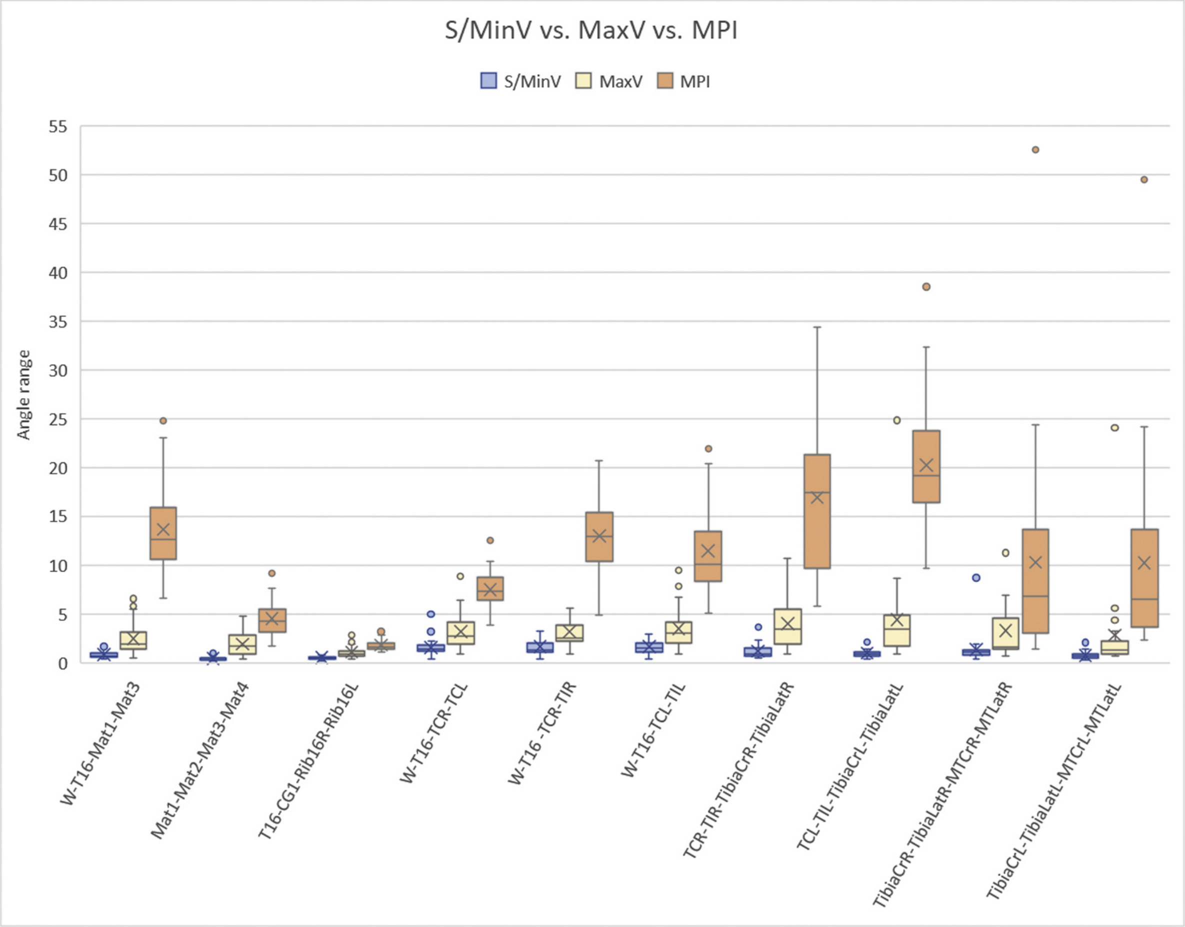

Fig. 6. Comparison of movements between measurements at stance/minimum volts (S/MinV—blue), maximum voltage used per horse and measurement day (MaxV—yellow) and manual pelvic inclination (MPI—brown) per angle range.

In addition, there was no difference in the ARs of the first and last data set of ES at the maximum voltage used in each horse. As mentioned before, fatigue is common with ES as it is inherently less efficient than voluntary produced movement [1]. This fatigue originates in the motor unit recruitment pattern of ES which is nonselective, spatially fixed, and has a temporally synchronous pattern [57]. On the contrary, voluntary muscle action does not recruit all motor units at the same time; at a given force level, additional motor units could be recruited when initially recruited units become fatigued [38]. In the user manual of the ES unit used in the present study, a longer duration of treatment than the duration used in the present study is recommended (35 minutes vs.

Table 6
Median (in brackets: minimum-maximum) values of angle ranges (see Fig. 5) and significance values (p) between the groups: stance/minimum volts (S/MinV), maximum voltage used per horse and measurement day (MaxV) and manual pelvic inclination (MPI).

Group/*P*-value	AR1	AR2	AR3	AR4	AR5	AR6	AR7	AR8	AR9	AR10
	W-T16-	Mat1-Mat2-	T16-CG1-	W-T16-	W-T16-	W-T16-	TCR-TIR-	TCL-TIL-	TibCrR-TibLatR-	TibCrL-TibLatL-
	Mat1-Mat3	Mat3-Mat4	Rib16R-Rib16 L	TCR-TCL	TCR-TIR	TCL-TIL	TibCrR-TibLatR	TibCrL-TibLatL	MTCrR-MTLatR	MTCrL-MTLatL
S/MinV	0.74 (0.40–2.11)	0.46 (0.18–0.99)	0.47 (0.18–1.51)	1.41 (0.42–4.97)	1.36 (0.44–5.00)	1.47 (0.42–4.99)	0.89 (0.46–3.66)	0.90 (0.44–2.37)	1.08 (0.40–8.72)	0.68 (0.29–2.09)
MaxV	1.95 (0.52–6.57)	1.75 (0.38–4.76)	0.92 (0.39–2.85)	2.72 (0.90–8.87)	2.57 (0.95–9.08)	3.02 (0.92–9.44)	3.48 (0.88–10.65)	3.43 (0.90–24.83)	1.66 (0.71–11.85)	1.30 (0.71–24.04)
MPI	12.68 (6.57–24.79)	4.28 (1.71–9.20)	1.61 (1.06–3.34)	7.32 (3.90–12.53)	12.98 (4.89–20.70)	10.09 (5.08–21.92)	17.39 (5.78–34.39)	19.21 (9.67–38.49)	6.78 (1.42–52.55)	6.57 (2.35–49.48)
p S/MinV versus MaxV	0.001	0.001	0.007	0.005	0.005	0.007	0.001	0.000	0.017	0.001
p MaxV versus MPI	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.001	0.033	0.009
p MPI versus S/MinV	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.002	0.000

The presented significance values for the comparison of these groups show significant differences for all three groups ($P < .05$).

20 minutes) [48], and it is possible that fatigue might develop with such longer durations. On the other hand, MPI led to pelvic inclination in all horses whereas ES did not lead to appreciable pelvic inclination in eight of ten horses on at least one of the MDs. The effect of fatigue may also not have been visible or measurable, because the training intensity was not very high. In addition, samples for measuring blood lactate and creatine kinase could have been gathered, although the training intensity and duration was most likely to low to alter those parameters.

As expected, BCS and SFT were strongly correlated. As BCS is a good indicator of body fat in horses [47] and illustrates body fat more accurately than other single physical measurements as, that is body mass (Henneke et al. 1983), it is closely related to SFT, which is a recognized marker for body fat in humans [58]. Although we could have measured skin and subcutaneous thickness using ultrasound directly in the area of application of electricity, it is easy to measure SFT on the neck in practice and this could therefore allow the selection of a useful current intensity for ES therapy. Contrary to expectations, neither SFT nor BCS were negatively correlated with either conductivity, voltage required, or ARs reached during ES. This is different in humans, where SFT interferes with the current intensity necessary to optimize the effectiveness of NMES [59] and subjects with thicker SFT require stronger NMES impulses than subjects with thinner SFT to achieve a desired contraction force [60].

The present study primarily aimed to document if and to which extent movement could be generated with this setting; therefore, preference was given to higher voltages. Future studies should repeat measurements several times at the lower voltages to facilitate the assessment of significant correlations between either conductivity or voltage used and changes in ARs produced. However, even for the present study, more measurements at stance without voltage applied might have allowed comparisons of these measurements with those of maximal ES. Measurements at stance were complicated by the fact that the horses tended to be nervous in the first few minutes and moved a lot during the initial measurement at stance; therefore, many of those measurements had to be excluded due to excessive movement; additional measurements at stance or/and measurements at stance after ES might have been an option.

The transmission of electricity through skin and subcutaneous tissues is determined by their physical characteristics, for example, the contact between skin and electrode gel. Electrode gel is needed for any penetration of electricity, as electrodes require a medium to transmit current [23]. The contact further depends on the coat, the angulation of the hair roots, and the coarseness of the skin as such. This is a phenomenon well known from ultrasound investigations of horses where skin preparation is paramount [61]. Clipping of the hair at the sites of electrode placement is recommended for many applications of electricity to coated or furry animals [23,62]. In this study, the coat of the horses was not clipped because the user manual of the ES unit used does not prescribe this [48]. Furthermore, owners will often object to such large areas being clipped and being obvious medium-term indications of the horse's need for treatment. Owing to the high number of horses that did not show any appreciable movement on at least one MD, maybe clipping the coat would nevertheless be indicated. Especially, as the hair coat is usually thickest over the dorsolateral aspects of the body [63] and the horses had a thick coat as measurements were conducted during winter and the horses were used to staying outside.

Once electricity has reached the skin surface, it has to pass through the stratum corneum, through the rest of the epidermis, containing living cells, through the dermis, and through adipose and connective tissue layers before reaching the motor nerve fibers [64]. Generally, the skin prevents electricity from entering the body—more than 99% of the body's resistance to electric current flow is at the skin [65]. The subcutis mainly consists of lipocytes [63]. It is known, that surface-stimulating electrodes direct current precisely beneath the surface area of the electrode, and because the current will travel through various qualities of subcutaneous tissue that create resistance, its strength will be diminished and the depth of penetration will be limited [1]. In humans, excessive subcutaneous fat thickness is an important limiting factor in the conduction of current from the skin to the target neurons, due to its high electrical resistance [66]. As conductivity is inverse to resistance [67], this is most likely contributing to the low conductivity values displayed in some of the horses. Suitably, the horse (H8) with the highest SFT and the highest BCS did not show positive conductivity values on two MDs, and it had only negative correlations between ARs and both volts and conductivity on the residual MD. These negative correlations may be associated with the attention created by the first sensation of the electricity being applied, which distracted the horse from its nervous movement observed before this sensation. Such a calming effect is also described in the user manual [48], but we could not observe this phenomenon over all horses. On the contrary to H3, the horse with the lowest BCS and the lowest SFT (H3) reached the highest conductivity value (4) as described previously. It is possible that the very excitable behavior of H3 during measurements (see supplementary files Table 1)—which led to exclusion of many of its measurements—is also associated with this lower resistance (due to less amount of body fat), which can cause discomfort [2].

The small number of horses used for testing clearly was a limitation for the present study, especially as some of them had to be excluded from electrical calculations due to lack of conductivity displayed. Three horses showed no displayed conductivity up to the pre-arranged maximum of 10 volts being applied through the stimulation pad at least at one MD, maximally at two MDs (H8 at MD2 and MD3). The ARs of these measurements without displayed conductivity were not taken into consideration, as it is highly doubtful that any changes in ARs seen in these horses were caused by ES. Under normal circumstances, the therapy session would be restarted, which was not possible due to the limitations of the ethics approval for the present study. Despite no conductivity being displayed on the ES unit, one horse appeared to show a mild, but rhythmical, inclination of the pelvis. This movement was comparable with the movements seen in the other horses and was nonetheless likely caused by the ES applied. Based on this, we cannot rule out that some ES may have occurred even though no conductivity was displayed. This puts into question the sensitivity of the conductivity measurement of the unit. Interestingly, in all of the three horses without conductivity on one or two MDs, conductivity was displayed on other MDs. This indicates that factors beyond subcutaneous tissue quality may be at play, such as technical issues (i.e., connection problems between back treatment pad and control unit) or inadequate moistening of the skin, or insufficient volumes of electrode gel, all of which are commonly known hindrances to electromyography [68].

The number of horses showing no appreciable movement despite ES of 10 volts was the highest on MD1 and lowest on MD3. This does not appear to be the consequence of an individual's characteristic although, as only one horse (H5) showed no appreciable movement on any of the three MDs despite moderate conductivity values being displayed. This horse was moving a lot independent of stimulation, which could of course have masked any movements produced by ES. The excessive movement of this horse led to exclusion of the corresponding measurements in most of the cases when ES was applied. It is possible, that horses initially counteracted the effect of ES by contracting the opposing muscle groups resulting in a stable pelvis position and after relaxing the opposing musculature, the movement then becomes apparent. An overall increased muscle tone may have a similar result. This is further supported by 3 horses which did only start to show movement after 10 volts had been applied repeatedly on MD1.

On the other hand, no difference between ARs at maximum voltage used could be shown between the MDs. In conclusion, this demonstrates that a (not significant) lower maximum voltage used on MD3 created the same amount of changes of ARs as was created by 10 volts on MD1. Owing to the small number of horses and measurements available for analysis, this needs to be proven in further studies.

No difference in lameness scores or muscle tone was found before and after stimulation, although this kind of therapy was shown to have positive effects on muscle spasticity [4,5,29]. This may most likely be due to the fact that no horses with clinically notable muscle disorders and more than mild lameness were used for the present study. In addition, every horse was only treated three times on alternate days or every third day, which may not be sufficient to cause changes. Pressure algometry could further contribute to objectively assess pain associated with increased muscle tone [69].

5. Conclusions

Electrical stimulation applied in the manner presented in the present study can produce significant movement of the horse. The movement originates from the lumbosacral region, but its effects can be documented in a much wider area. However, the movement produced is much smaller than the movement that can be generated via MPI. Those disparities show the difference in possible benefits of these methods. While MPI protocols used for physical therapy have been described to have more of a stretching effect, ES of the lumbosacral region has more likely initially a mobilizing and later a training effect on the muscles in this area as well as on muscles of the hind limb. This underlines the possible use of this system in stabilizing the sacroiliac joint and training quadriceps muscles. In future, horses with lumbosacral and or iliosacral pathologies could be selected for testing to draw more valid conclusions regarding the efficacy of this physiotherapeutic modality to develop suitable treatment plans.

CRediT authorship contribution statement

Daniela C. Riedler: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Visualization. **Rebeka R. Zsoldos:** Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision. **Matthias Robel:** Investigation, Writing - review & editing. **Isabelle D. Jobst:** Investigation, Writing - review & editing. **Theresia F. Licka:** Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft, Supervision.

Acknowledgments

Dr. Sheila Schils (Cofounder of EquiNew LLC.) provided the authors with the FES310 unit for electrical stimulation for the duration of the data collection of this study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jevs.2020.103116.

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