Journal of Equine Veterinary Science 68 (2018) 73–80

Contents lists available at ScienceDirect

Journal of Equine Veterinary Science

journal homepage: www.j-evs.com

Original Research

The Efficacy of Intermittent Long-term Bell Boot Application for the Correction of Muscle Asymmetry in Equine Subjects

Anne-Mette Jensen, Waqas Ahmed, Vibeke S. Elbrønd, Adrian P. Harrison*

IVH, Faculty of Health & Medical Sciences, Copenhagen University, Copenhagen, Denmark

ARTICLE INFO

Article history:
Received 7 February 2018
Received in revised form
2 May 2018
Accepted 21 May 2018
Available online 26 May 2018

Keywords:
Acoustic myography
Lameness
Training
Proprioception
Tactile stimulation

ABSTRACT

It has been proposed that manipulating proprioceptive signals of the equine distal limb as part of a rehabilitation process in cases of musculoskeletal pain or neurologic deficits can be used to correct postural control and restore normal motor programs. This trial has examined the effect of treatment with a light-weight and loose-fitting bell boot (82 g) on an imbalance of *muscle gluteus superficialis* function in horses as measured using acoustic myography (AMG). Eight horses were trained over a 60-minute period every 3 days for 6 weeks, a protocol based on preliminary findings. Acoustic myography measurements, recording the coordination, spatial and temporal summation of muscle contractions, were made at the start (baseline) and at the finish (week 6) after a warmup period and following a set procedure of physical activity. Walking, trotting, and cantering during a left-hand circle at the start of the trial revealed a slight but significant asymmetry between the left and right hind limb muscle, which improved successfully after 6 weeks of proprioception training. Data for the right-hand circle, which revealed no significant asymmetry, during walk, trot, and canter at the start, showed no change after 6 weeks of training at the walk and trot but developed an imbalance during cantering, the result of overcompensation. This study demonstrates that functional musculoskeletal asymmetry measured during periods of activity can not only be accurately detected using AMG but it also reveals an association between the program of proprioceptive training adopted and an improvement in muscular imbalance.

1. Introduction

Lameness is a primary cause of loss and euthanasia in the equine industry, and both the diagnosis and treatment of this type of injury is often time consuming and expensive [1,2]. Studies suggest that compensation and redistribution of weight, due to pain or tension, can cause repetitive strain injuries, as the additional load overstresses ligaments, muscles, and bones throughout the body [3–6]. To reduce any risk of loss of performance, it is considered beneficial to avoid the progression of muscular imbalance to help avoid a compensatory injury and the resulting lameness [2,7–9].

Proprioception is the sense of the relative position of one's own body parts and the physical effort used at rest and during movement [10]. It is generally accepted that cutaneous receptors contribute directly to proprioception by providing “accurate perceptual information about joint position and movement,” knowledge that is combined with information from the muscle spindle receptors (intrafusal fibers) of muscles and the golgi tendon organs [11]. Proprioception is known to improve with repeated stretching exercises, in particular, those designed to stimulate the central nervous systems (CNSs) primary input fields such as mental status and sensory input from a subject's surroundings [12].

A study performed by Clayton et al suggests a new form of therapeutic treatment intended to activate the hind limbs to a greater extent and thereby remove any imbalance during the engagement of these limbs [13]. These authors observed the reaction of horses to the application of different tactile stimuli at the

---

Animal welfare/ethical statement: The horse owners were informed about the study and were able to see the measuring setup and ask questions in a private setting before consenting to participate. There was no ethical issue in this study because all the subjects were healthy. Moreover, the measuring equipment used complied with both Conformité Européenne and Federal Communications Commission regulations and was noninvasive in its nature. The study was carried out according to the guidelines laid out in the Helsinki Declaration (https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/).

Conflict of interest statement: APH is currently trying to commercialize the AMG recording system and is establishing a company to cover the costs of future development.

* Corresponding author at: Adrian P. Harrison, IVH, Faculty of Health & Medical Sciences, Copenhagen University, Gronnegaardsvej 7, DK-1870, Frederiksberg C, Denmark.

E-mail address: adh@sund.ku.dk (A.P. Harrison).

https://doi.org/10.1016/j.jevs.2018.05.214
0737-0806/

level of the hind pasterns and found that light-weight chains stimulated the cutaneous mechanoreceptors in the coronet and pastern with a positive effect on the swing phase of each stride. This interesting finding that tactile stimulation of the pastern can have a therapeutic effect in horses may prove to be applicable in the treatment of functional muscle asymmetry and disuse atrophy. Furthermore, developments in modern technology have recently made it possible to measure muscle activity in a noninvasive fashion by means of acoustic myography (AMG) [14,15]. These findings combined with the new technology of AMG now provide an opportunity to study cutaneous mechanoreceptor stimulation's effect on muscle activity in horse limbs over time, as a means of reducing the risk of strain injuries arising from muscular imbalance.

As AMG in veterinary medicine, and especially horses, is not well known, a brief summary of the technique and analysis seems relevant. AMG uses an ESTi score, which represents the (integrated) mean of the E-, the S-, and the T-scores for a muscle to assess muscle function. If both ESTi scores for the left- and right-hand sides of a subject are more or less equal, then there is no or minimal imbalance in terms of force production. The E-score represents the efficiency with which a contraction occurs, strictly it measures the time a muscle is active compared to the inactive phase, so a low E-score indicates a muscle that is active longer than a fit muscle would be for the same activity, for example, during periods of canter. The S-score represents spatial summation, that is to say the way the CNS generates muscle force (or one of them). With spatial summation, the CNS decides how many muscle fibers to activate for any given contraction. This presents itself on the AMG recording as the amplitude of the signal. For ease of interpretation, the spatial summation parameter (amplitude) has been inverted; thus, a high S-score means few fibers active and a low amplitude. A low S-score means the opposite, many fibers active and a high signal amplitude. The other way in which the CNS generates force is by means of temporal summation (T-score). Here, the firing rate of those fibers that are active is controlled and adjusted. If the CNS fires fibers faster and faster they produce more force, effectively they have less time to fully relax. This parameter has also been inverted for ease of interpretation. Thus, a high T-score represents a low firing frequency, and a low T-score means the opposite, namely a high firing frequency.

Thus, when the CNS commences force production in a muscle, it estimates both the number of fibers to be activated and the rate at which they should be fired and for how long. Usually, the CNS overestimates both parameters when initiating a contraction in a muscle and fine tunes both parameters immediately after the start of force production [16,17]. This mechanism not only serves to conserve energy but also delays the onset of fatigue during periods of sustained contraction. The E-score, or measurement of efficiency, coordination, and synchrony, improves with training [18]. With repeated contractions, the CNS becomes more efficient at activating fibers at precisely the same time by reducing the braking and resistance effect of antagonistic muscles, which serve to counterbalance muscle contractions and limb movements, for example, the human upper arm muscles biceps and triceps are antagonists. Often in a poorly trained or unfit individual, an antagonist muscle is not fully relaxed during the contraction of an agonist muscle, forcing the active muscle to work harder. With repeated training, the CNS becomes more efficient at “switching off” antagonistic muscles at exactly the point during muscle contraction that an agonist muscle becomes active. Thus, an AMG ESTi score provides an overview of the efficiency of contraction, the number of active fibers, and the firing rate. When the ESTi scores differ, one should look to see why. Is it perhaps the result of a higher S-score, which means fewer active fibers, a higher T-score, which means a lower firing frequency, or is it the result of a higher E-score, which means a more efficient contraction.

The aim of this study has therefore been to examine the effect of treatment with a light-weight and loose bell boot on the imbalance of *muscle gluteus superficialis* in horses as measured using AMG. This study has tested the following hypotheses: (1) functional asymmetry in *m. gluteus superficialis* of exercised horses can be measured using AMG and (2) the use of a light-weight and loose bell boot over a period of weeks can rectify an imbalance in the hind limbs, as assessed by *m. gluteus superficialis* function measured using AMG.

2. Materials and Methods

2.1. Subjects

Eight healthy equine subjects, being defined as horses with no clinical or performance history of lameness, six geldings aged 6–15 years (mean ± standard deviation [SD]; 9.5 ± 3.3), and two mares aged 7 years (mean ± SD; 7.0 ± 0.0), were measured using AMG for muscle function of *m. gluteus superficialis* during walking, trotting, and cantering for both a left-hand circle and right-hand circle. The muscle selected for this trial has the function of flexing the hip as well as protracting and abducting the hind limb.

All eight horses selected, including the two horses used in the preliminary trial, received a lameness evaluation (AMJ, WA), which included assessment for palpable abnormalities (thickening, swelling, etc.; VSE). The horses were evaluated while moving at the walk and trot on a straight line and walk, trot, and canter lunging. In addition, horses were assessed in terms of complaints by their owners with regard to poor performance issues. The horses, which were used for dressage competitions at the level of amateur, were in full work and did not have a previous history of injury or orthopedic problems.

2.2. Ethics

There was no ethical issue in this study because all the subjects were healthy. Moreover, the measuring equipment used complied with both Conformité Européenne and Federal Communications Commission regulations and was noninvasive in its nature. The study was carried out according to the guidelines laid out in the Helsinki Declaration (https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/). The AMG measurements can be compared to holding a microphone (sensor) against the skin. The only adverse effect could be allergy against ultrasound gel, which is applied under the sensor. The horses were recruited via advertising of flyers in stables close to Copenhagen, and the horse owners gave their informed consent after reading a brief description of the study and before the start of any measurements. While the AMG data were collected for the eight horses recruited in this study, additional data concerning the horses' owner were also necessary (owners name [indicating gender], address, phone number, e-mail contact). This human data were handled according to the Act on Processing of Personal Data (Act No. 429 of 31 May 2000 with amendments [latest 2007]) implementing Directive 95/46/EC on the protection of individuals with regard to the processing of personal data and on the free movement of such data.

2.3. AMG Recordings

The AMG technique is a noninvasive and pain-free means of recording muscle contractions transdermally [14,15].

An AMG recording unit (product name CURO) attached to a sensor, having a diameter of 50 mm, and coated with acoustic gel (MyoDynamik ApS, Frederiksberg C, Denmark) was used for AMG recordings. The AMG parameters determined were efficiency (E-score) as well as both spatial and temporal summation during force production expressed by the S- and T-score of the combined ESTi score (MyoDynamik ApS, Frederiksberg C, Denmark). The E-parameter corresponds to the time periods of active/inactive function relative to the duration of the activity period of the muscle (how long the muscle is “on”: thus [0.50 seconds–0.15 seconds]/0.50 seconds × 10 = an E-score of 7.0). The S-parameter reflects the recruitment of motor units and equates to signal amplitude (how many motor units are active). For the present study, the S-parameter was determined as the signal amplitude in relation to a full 6 dB signal (measured as approx. 1 V; thus [0.99V–0.44V]/0.99V × 10 = an S-score of 5.5). The T-parameter represents the motor unit firing rate or signal frequency (how fast the motor units are firing) and was expressed in relation to a set maximal firing rate for *m. gluteus superficialis* (120 Hz: thus [120Hz–78 Hz]/120 Hz × 10 = a T-score of 3.5). The sensor was placed over the muscle body for the muscle of interest using a self-adhesive bandage (Co-Plus LF; BSN medical GmbH, Hamburg, Germany). The sensors for the *m. gluteus superficialis* measurements were placed by the same experienced person (AMJ) using visible cues. When stimulating a reflex just dorsally to the tuber coxae, extending the hip, the outline of the *m. gluteus superficialis* appeared as a ridge enabling the precise placement of the sensor in relation to the underlying muscle structure. Furthermore, it has been shown that the placement of an AMG sensor on different locations of an active muscle gives identical E-, S-, and T-score, representing as it does the contractile vibrations of the tissue as a whole [15]. Both AMG measurements, the initial baseline and the final recording, were made without a light-weight bell boot present on the weaker leg. Horses were warmed up initially over a 16-minute period, after which an AMG measurement was made while the horse was physically active, following a set procedure of 1-minute walk, left rein; 1-minute walk, right rein; 1-minute trot, left rein; 1-minute trot, right rein; 1-minute canter, left rein; and 1-minute canter, right rein.

2.4. Experimental Design

A total of eight horses were measured using AMG. The sample size adopted in this study was derived based on a Power Analysis (InStat 3 for Mac, Version 3.0b, 2003; Graph- Pad Inc., La Jolla, CA) of AMG data collected for this particular muscle from a much larger cohort of horses. The weight of the horses was approx. 557 ± 102 kg (range 350–700 kg). The average height at the withers of the horses in this study was 163 ± 7.8 cm (range 149–175 cm). The horses were measured at the walk, trot, and canter lunging on a 20-m circle over an arena surface to the left and right.

The weaker leg was defined as the one that was the least engaged, in other words, the one with the highest ESTi score. The definition of a slight imbalance was taken as being a maximum delta of 5 (see Fig. 2 baseline canter) left versus right using the ESTi score from the AMG measurement as described previously.

The weight of the loose bell boot was 82 ± 1g, which in terms of average body weight was (82/557,000 g) 0.014%; this equates to a weight around the ankle of an average 70 kg human of 9.8 g, the same weight as a single sheet of an A4 paper. In the study by Clayton et al. (2010), a stimulation device (weighing 55 g) comprising a braided strap with lightweight brass chains placed around the pastern was used to activate proprioception. In our hands, a similar approach resulted in the stimulation device moving to the rear of the hoof during periods of physical activity, and a weighted bell boot was subsequently adopted for reasons of repeatability and accuracy, as well as noticeable activation of proprioception in a preliminary trial. The weighted bell boot was of a neoprene material (www.Biltema.dk) and was fixed loosely to the weaker leg; the size selected was “cob” (see Fig. 1). Training with the bell boot (placed on the weakest leg) comprised 60 minutes of regular exercise every 3 days for a period of 6 weeks. The riding exercise performed was the horse's normal routine, and this was undertaken by the owner. The loose-fitting bell boot was used with every second training session so as to reduce the risk of habituation. In between bell boot training sessions, the horses were trained routinely by their owners without the aid of a bell boot.

2.5. AMG Analysis

The AMG data in this study were analyzed in terms of their individual E-, S-, and T-parameters for each subject [13]. The S-score was determined as the signal amplitude in relation to a full 6 dB signal (0.1 mV), while the T-score was determined as the frequency in relation to a Max T value (120 Hz). Each score was expressed on a scale of 10 to 0, where 10 is most optimal and 0 is least optimal for each parameter—for example, an S-score of 9 represents an AMG signal with a very small amplitude, while a T-score of 2 represents a relatively high firing frequency. The ESTi score was calculated as the delta between the E-, S-, and T-parameters for the left and right hind limb muscle measurements. An efficient and fit muscle has a small amplitude signal (high S-score), a low firing frequency (high T-score), with a high degree of efficiency/coordination (high E-score) corresponding with an integrated ESTi score that is relatively high [15,18,19]. The ESTi score can also be used to quantify any difference between the left and right sides in the form of a Δ value; left E = 5; S = 6; T = 3—right E = 6; S = 3; T = 2, for example (5 + 6+3–6–3–2) = Δ3 ESTi.

2.6. Statistical Analysis

Data were initially tested for normal distribution and equal variance. Differences between means were tested for statistical significance using GraphPad InStat 3 for Mac (Version 3.0b, 2003; GraphPad Inc., La Jolla, CA) and a paired *t* test. Differences between means with a *P* value > .05 were considered nonsignificant (NS). Values are presented as the mean ± the SD of the mean.

3. Results

3.1. Repeatability of the AMG Measurements

The AMG signal recorded by the CURO unit has proved to be not only very stable and accurate but also very repeatable [14,15]. It was found that the SDs of the recorded parameters were very similar when comparing values at the beginning (week 0) and finish (week 6) of this study (see Table 1), for example, T-score for left rein, left muscle baseline of 9.0 ± 0.3 versus right rein, left muscle of 8.7 ± 0.4 and right rein week 0 of 8.7 ± 0.4 versus week 6 of 8.4 ± 0.5.

In particular, the T-score, which measures the rate at which the muscle contractions occur (temporal summation), was found to have a very consistent mean ± SD and a very narrow range maximum to minimum for the horses measured at specific gaits, for example, 9.0 ± 0.3—maximum 9.3 and minimum 8.4—left-hand circle, canter. With the increasing muscle work associated with a change in gait, there was a greater variation in the measured parameters, in particular the E- and the S-score revealing individual differences in performance level between subjects. It was also noted that the ESTi score values decreased with increasing physical

Fig. 1. A photo of the bell boot used in this study. A neoprene bell boot was fixed loosely to the weaker leg; the size selected was "cob."

activity, indicative of increased muscle activation with increased work, for example, right-hand circle baseline shows a shift from walk 7.0 ESTi to trot 5.0 ESTi to canter 4.6 ESTi (see Fig. 3).

3.2. Left-Hand Circle

The AMG data for horses walking revealed a significant difference in muscle activity between the left and right hind limb muscles (*m. gluteus superficialis*), which improved after 6 weeks of proprioception training with the light-weight and loose bell boot adopted for this study (see Fig. 2).

Walk—for *m. gluteus superficialis*, there was a significant ESTi score imbalance of 2.7 (S-score $P < .05$), which after 6 weeks of bell boot training was measured as improving to 1.3 imbalance (NS).

Trot—for *m. gluteus superficialis*, there was a significant ESTi score imbalance of 4.5 (S-score $P < .05$, T-score $P < .05$), which after 6 weeks of bell boot training was measured as improving to just 1.0 imbalance (NS).

Table 1
The mean (±SD) of the E-, S-, and T-score values for all eight horses at week 0 (Baseline) compared with week 6 (*Finish*) for both the left and right *m. gluteus superficialis* and for the left and right reins.

Left-Hand Circle (Rein)						Right-Hand Circle (Rein)					
	–	Week 0 (Baseline)		Week 6 (Finish)			–	Week 0 (Baseline)		Week 6 (Finish)	
		Mean	SD	Mean	SD			Mean	SD	Mean	SD
Left muscle						Left muscle					
Walk	E	5.6	1.8	6.0	1.3	Walk	E	5.2	2.1	5.1	1.7
	S	8.5	0.5	7.5	1.4		S	8.6	0.4	7.2	1.8
	T	7.1	0.9	7.4	1.4		T	7.0	1.2	6.9	2.1
Trot	E	2.6	2.5	2.1	0.9	Trot	E	3.0	2.3	1.7	0.6
	S	6.4	1.2	4.4	2.2		S	6.1	1.5	4.0	2.6
	T	8.4	0.4	8.4	0.5		T	8.6	0.4	8.4	0.5
Canter	E	2.3	1.9	1.7	1.3	Canter	E	2.0	2.5	0.7	0.5
	S	4.8	1.4	3.4	2.4		S	3.7	2.1	2.3	2.1
	T	9.0	0.3	8.7	0.5		T	8.7	0.4	8.4	0.5
Right muscle						Right muscle					
Walk	E	4.1	2.6	5.3	2.1	Walk	E	4.6	2.0	4.9	1.5
	S	8.1	0.7	7.4	1.5		S	8.3	0.6	7.5	1.7
	T	6.4	0.8	6.9	0.9		T	6.4	1.3	7.0	1.4
Trot	E	1.1	0.8	1.7	1.2	Trot	E	2.5	1.0	2.1	0.9
	S	4.2	2.7	4.2	2.7		S	5.2	2.4	4.6	2.7
	T	7.7	0.6	8.4	0.4		T	8.2	0.5	8.4	0.7
Canter	E	0.4	0.3	1.3	1.3	Canter	E	2.1	1.7	2.1	0.8
	S	2.5	1.9	2.7	2.6		S	3.5	2.4	3.4	2.5
	T	7.9	1.0	8.6	0.4		T	8.7	0.3	8.9	0.2

SD, standard deviation.

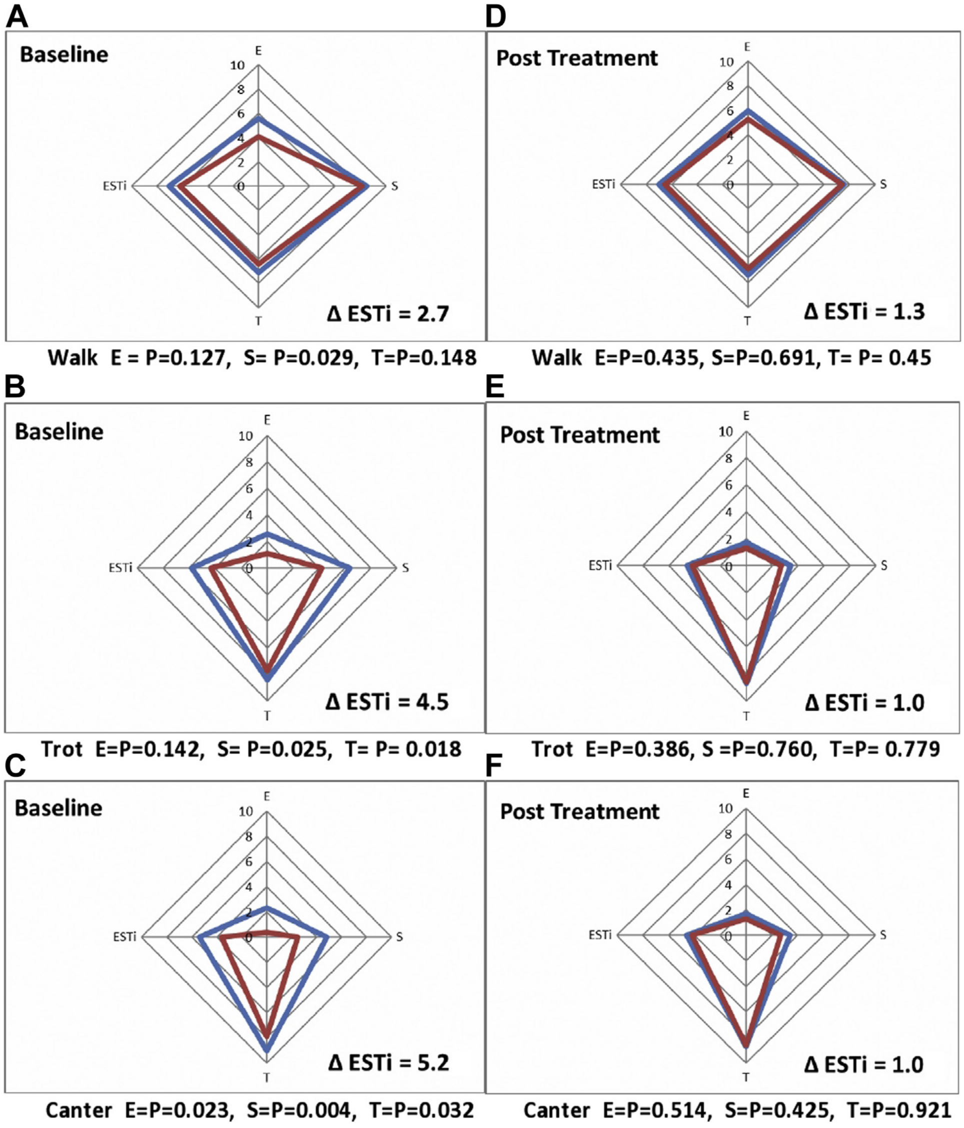

Fig. 2. Radar plots for the E-, S-, and T-scores as well as the combined ESTi score for *m. gluteus superficialis* measured during walking (A and D), trotting (B and E), and cantering (C and F) on a left-hand circle. Values are the mean of n = 8 horses. Note that the blue radar plot is for the left-hand side and the red radar plot is for the right-hand side of the horse.

Canter—for *m. gluteus superficialis*, there was a significant ESTi score imbalance of 5.2 (E-score $P < .05$, S-score $P < .01$, T-score $P < .05$), which after 6 weeks of bell boot training was measured as improving to just a 1.0 imbalance (NS).

3.3. Right-Hand Circle

Walk—for *m. gluteus superficialis*, there was a nonsignificant ESTi score imbalance of 1.5, which after 6 weeks of bell boot training was measured as improving to just a 0.2 imbalance (NS; $P > .05$ for E-, S-, and T-scores alike) (see Fig. 3).

Trot—for *m. gluteus superficialis*, there was a nonsignificant ESTi score imbalance of 1.7, which after 6 weeks of bell boot training was measured as an imbalance of 1.1 (NS; $P > .05$ for E-, S-, and T-scores alike).

Canter—for *m. gluteus superficialis*, there was a nonsignificant ESTi score imbalance of 0.1 ($P > .05$ for E-, S-, and T-scores alike), which after 6 weeks of bell boot training was measured as worsening to a significant imbalance of 3.0 (E-score $P < .01$, S-score $P < .01$).

4. Discussion

To the best of the authors' knowledge, this is the first study to examine the effects of manipulating proprioception with tactile stimulation over a period of time on muscle function and asymmetry with respect to training and potentially reducing the risk of strain injuries in exercising horses arising from just such an imbalance.

On a critical note, no controls were incorporated in this study, making the findings potentially speculative, in that one could argue that corrective changes in balance may well have occurred over time without any form of intervention. However, the findings of Clayton et al [13] speak against this line of reasoning, as do a number of corrective tests with horses (data not shown), in which we have found that the use of a light-weight bell boot on horses presenting with mild lameness or gait issues can be almost immediately corrected. Other confounding variables could potentially include (1) muscle injury (gradual repair), (2) sensor location, and (3) the frequency of bell boot use. It is possible that all eight horses in this study had a minor muscle sprain in the “weaker” limb

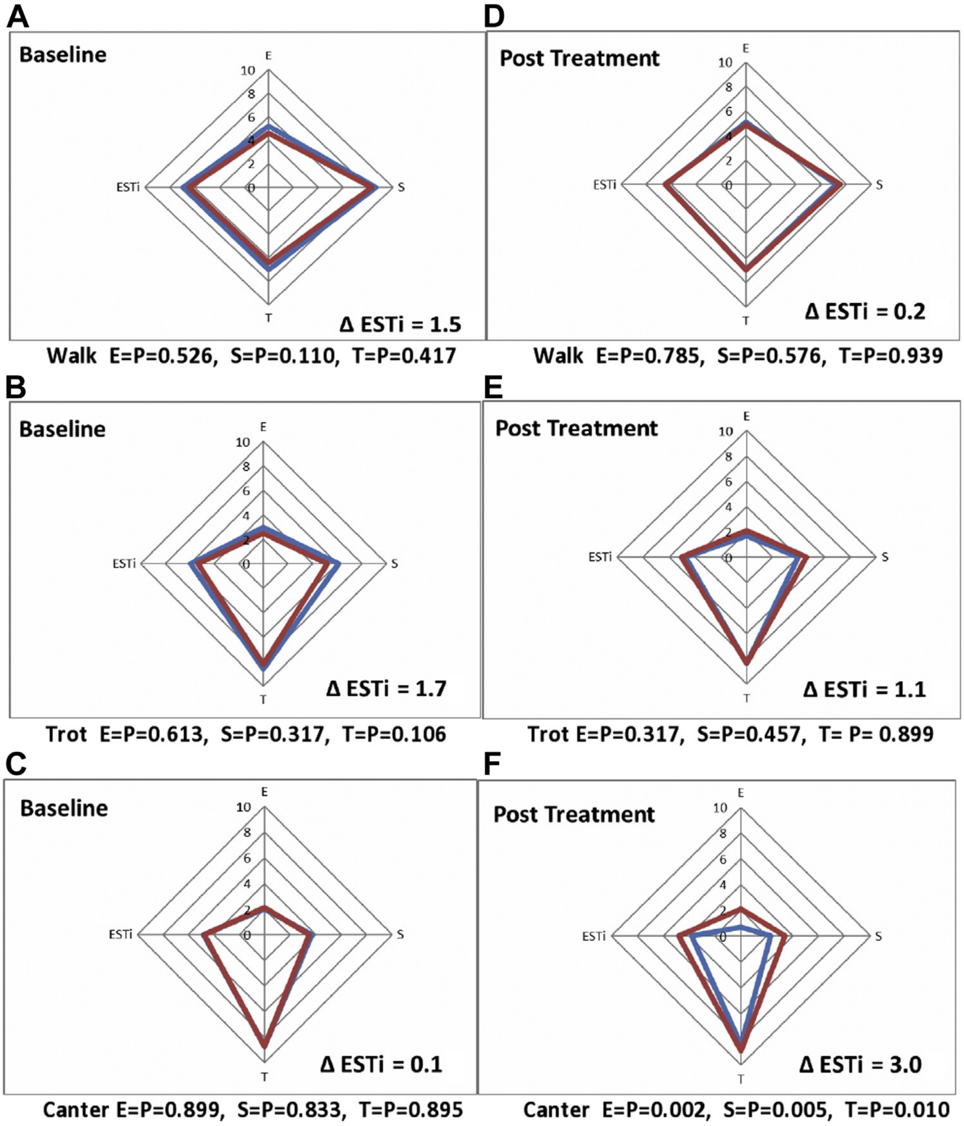

Fig. 3. Radar plots for the E-, S-, and T- scores as well as the combined ESTi score for *m. gluteus superficialis* measured during walking (A and D), trotting (B and E), and cantering (C and F) on a right-hand circle. Values are the mean of n = 8 horses. Note that the blue radar plot is for the left-hand side and the red radar plot is for the right-hand side of the horse.

that was not detected, and that over the period of this study, muscle repair occurred such that the initial imbalance was resolved. However, this goes against the findings in this study that the SDs for the E-, S-, and T-scores were very comparable at the start and finish of this trial. With regard to sensor location, we know that even if the sensor is placed on a slightly different region of the muscle of interest that an identical AMG signal is measured [15], it is measuring pressure waves after all and not an electrical signal affected by the innervation site as with surface electromyography (sEMG). In terms of the frequency of use of the light-weight bell boot, we have no certainty that the horse owners followed the training program rigorously, only their word that this was done.

The data from this study show a fall in the ESTi score with the increased muscle work associated with the change in gait from walk to trot and from trot to canter (see Figs. 2 and 3). In addition, our data reveal that the T-score improves with a change in gait from walk to trot and a further albeit very slight improvement from trot to canter. This change in the T-score has been shown previously as being related to the transition from potential/kinetic energy associated with slower gaits, toward more elastic recoil energy found with faster gaits such as trot and canter, referred to as the mass-spring model [19].

The present results show a clear, albeit slight, imbalance for *m. gluteus superficialis* of the eight horses in this study. The left hind limb was found to be the weakest, showing a poorer level of engagement during walking, trotting, and cantering for the left-hand circle (rein). The significance of this degree of imbalance and its duration need further study, although it has been stated that muscle pain and injury as a cause of poor performance and lameness in the horse is poorly recognized [8]. Indeed, lameness, as a symptom, can originate from something as simple as repetitive strain injuries [2], which could themselves arise from a simple imbalance over time. It is known that sound horses measured using a pressure plate show a high degree of symmetry in terms of ground reaction force at the walk and trot [20], presumably because of balanced and coordinated muscle contractions in their left and right limbs. Likewise, lameness in a horse can be measured through analysis of the kinetic gait with the aid of a static force plate [21], although such diagnostic tests can prove challenging, time consuming, and expensive. Ishihara et al showed that lame horses exhibited a higher vertical peak force in the contralateral hind limb to the one that was clinically lame using just such a diagnostic tool [19]. Alternatively, one can try to measure muscle imbalance directly in horse muscles using sEMG [7]. While there are issues with the accuracy of sEMG when assessing muscle function [7,15,22], an analysis of equine gluteal muscles revealed a significantly greater ratio for the max-mean signal activity during walking and trotting between lame and healthy (nonlame) horses [7]. These authors concluded that differences between nonlame and lame horses (chronic unilateral pelvic limb lameness) in terms of pelvic limb muscle activity could be detected using sEMG [7]. An increased signal activity in muscles of horses that are lame compared with healthy horses can be seen as overusing specific muscles during such gaits as walking and trotting. It is known that overuse exercise of muscles can result in the inability of weaker fibers to regenerate adenosine triphosphate and hence enter a fixed cross-bridge cycling state (e.g., just after the power stroke, where myosin is in a low-energy state, before unbinding of myosin and actin) [23,24]. Thus, as stiffness of such weak fibers increases, mechanical disruption is expected to occur as a result of subsequent muscle stretch [23], also referred to as sarcomere popping [25].

It is interesting that such a slight imbalance as 2.7 to 5.2 for the ESTi score from walk to canter can be improved through the use of a light-weight and loose bell boot over a period of 6 weeks of intermittent use (see Fig. 2; 1.3–1.0 for the ESTi score from walk to canter). Thus, the AMG data reveal that bell boot training with a weight as slight as approx. 80g (0.014% of body weight) had a significant effect on the weak left hind limb and hind limb balance overall. The results of this study further show that with this approach, the left hind limb becomes more engaged/active (lower ESTi score), and the inherent imbalance is greatly reduced to the point of being nonsignificant. A detailed analysis indicates that this is achieved through greater fiber activation (lower S-score) and through a more intense fiber activity (lower E-score) with both hind limb muscles becoming more coordinated.

For the right-hand circle, the data reveal no dramatic changes for the walk or trot. However, the canter data for the right-hand circle reveal an imbalance that occurs when a weaker left hind limb is engaged through proprioception in addition to the activity of powering the horse through the right-hand circle. This loss of balance seen during the right-hand circle (rein) after training for the left hind limb during periods of canter is most likely a form of overcompensation to the proprioception regimen [12]. It is documented that adaptations occur in muscles and joints as the result of disturbances induced by training itself [26]. Moreover, perturbation training in human subjects has revealed alterations in muscle cocontraction and increased peak flexion of joints [27]. These changes are thus most likely grounded in kinematic alterations in response to the training protocol adopted in this study and the improved hind limb balance, observations reported first by Dr Vladimir Janda exploring sensorimotor training in connection with patterns of muscle imbalance [28]. Indeed, it was Dr Janda who was the first to propose proprioception as part of the rehabilitation process, with implications for equine locomotor pathology, using sensorimotor training to emphasize correct postural control and gradually restore normal motor programs in patients [2].

It is concluded that a slight musculoskeletal imbalance during periods of activity (walk, trot, canter), which is believed through altered stress to induce tissue strain and over time subsequent injury leading to lameness [2], can not only be accurately detected using AMG but can also be corrected through a program of proprioceptive training. The regimen of 60 minutes use a single light-weight bell boot every 3 days for a period of 6 weeks applied to the weakest limb, that is to say the one that is least engaged has a significant and positive effect on equine hind limb imbalance. Whether this corrective change induced through proprioceptive activation can be maintained permanently now remains to be established.

Acknowledgments

WA was supported by a PhD grant from Pakistan under the The Punjab Education Endowment Fund program. The authors are indebted to the kind help shown by Dr Kent Allen and Dr Jill Costello of Virginia Equine Imaging for proof reading this article and providing suggestions for improvement.

Authors' contributions: AMJ and APH designed the study. AMJ carried out the measurements. All authors participated in the data handling and writing of the article.

References

[1] Egenvall A, Penel JC, Bonnett BN, Olson P, Pringle J. Mortality of Swedish horses with complete life insurance between 1997 and 2000: variations with sex, age, breed and diagnosis. Vet Rec 2006;158:397–406.

[2] Schwanda M, Peham C. Changes in stride parameters caused by induced supporting limb lameness in trotting horses on a treadmill. Wien Tierarztl Monatsschr 2013;100:181–7.

[3] Greve L, Dyson S. The horse–saddle–rider interaction. Vet J 2013;195:275–81.

[4] Hood DM, Wagner IP, Taylor DD, Brumbaugh GW, Chaffin MK. Voluntary limb-load distribution in horses with acute and chronic laminitis. Am J Vet Res 2001;62:1393–8.

[5] Weishaupt MA, Wiestner T, Hogg HP, Jordan P, Auer JA. Compensatory load redistribution of horses with induced weight-bearing forelimb lameness trotting on a treadmill. Vet J 2006;171:135–46.

[6] Buchnefp H, Savelberg HHCM, Schamhardt HC, Barneveld A. Temporal stride patterns in horses with experimentally induced fore-or hindlimb lameness. Equine Vet J 1995;27:161–5.

[7] Zaneb H, Kaufmann V, Stanek C, Peham C, Licka TF. Quantitative differences in activities of back and pelvic limb muscles during walking and trotting between chronically lame and nonlame horses. Am J Vet Res 2009;70:1129–34.

[8] Turner T. Muscle injury detection and therapies. http://www.turnerequinesportsmed.com/muscle-injury-detection-and-therapies/01-5-2017. Accessed November 4, 2017.

[9] Dyson S. Lameness and poor performance in the sport horse: dressage, show jumping and horse trials. J Equine Vet Sci 2002;22:145–50.

[10] Lephart SM, Pincivero DM, Giraido JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med 1997;25:130–7.

[11] Collins DF, Refshauge KM, Todd G, Gandevia SC. Cutaneous receptors contribute to kinesthesia at the index finger, elbow, and knee. J Neurophysiol 2005;94:1699–706.

[12] Frick A. Stretching exercises for horses: are they effective? J Equine Vet Sci 2010;30:50–9.

[13] Clayton HM, White AD, Kaiser LJ, Nauwelaerts S, Lavagnino M, Stubbs NC. Hindlimb response to tactile stimulation of the pastern and coronet. Equine Vet J 2010;42:227–33.

[14] Harrison AP, Danneskiold-Samsøe B, Bartels EM. Portable acoustic myography—a realistic noninvasive method for assessment of muscle activity and coordination in human subjects in most home and sports settings. Physiol Rep 2013;1:1–9.

[15] Harrison AP. A more precise, repeatable and diagnostic alternative to surface electromyography—an appraisal of the clinical utility of acoustic myography. Clin Physiol Funct Imaging 2018;38:312–25.

[16] Harrison AP, Nielsen AH, Eidemak I, Molsted S, Bartels EM. The uremic environment and muscle dysfunction in man and rat. Nephron Physiol 2006;103:33–42.

[17] Dideriksen JL, Enoka RM, Farina D. Neuromuscular adjustments that constrain submaximal EMG amplitude at task failure of sustained isometric contractions. J Appl Physiol (1985) 2011;111:485–94.

[18] Bartels EM, Harder A, Salomons Heide K, Pingel J, Torp Andersen I, Harrison AP. The Use of acoustic MyoGraphy as a measure of training effects in Athletes- a 10 Month case study of a BMX rider. Ann Sports Med Res 2017;4:1–5.

[19] Fenger C, Harrison AP. The application of acoustic myography in canine muscle function and performance testing. SOJ Vet Sci 2017;3:1–6.

[20] Oosterlinck M, Hardeman LC, Van Der Meij BR, Veraa S, Van Der Kolk JH, Wijnberg ID, Pille F, Back W. Pressure plate analysis of toe-heel and medio-lateral hoof balance at the walk and trot in sound sport horses. Vet J 2013;198:9–13.

[21] Ishihara A, Reed SM, Rajala-Schultz PJ, Robertson JT, Bertone AL. Use of kinetic gait analysis for detection, quantification, and differentiation of hind limb lameness and spinal ataxia in horses. J Am Vet Med Assoc 2009;234:644–51.

[22] Williams JM. Electromyography in the horse: a useful technology? J Equine Vet Sci 2018;60:43–58.

[23] Kim J-S, Hinchcliff KW, Yamaguchi M, Beard LA, Markert CD, Devor ST. Exercise training increases oxidative capacity and attenuates exercise-induced ultrastructural damage in skeletal muscle of aged horses. J Appl Physiol 2005;98:334–42.

[24] Lieber RL, Friden J. Selective damage of fast glycolytic muscle fibres with eccentric contraction of the rabbit tibialis anterior. Acta Physiol Scand 1998;133:587–8.

[25] Morgan DL, Proske U. Popping sarcomere hypothesis explains stretch-induced muscle damage. Clin Exp Pharmacol Physiol 2004;31:541–5.

[26] Gruber M, Gollhofer A, Bruhn S. Specific adaptations of neuromuscular control and knee joint stiffness following sensorimotor training. Int J Sports Med 2006;27:636–41.

[27] Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. Phys Ther 2005;85:740–9.

[28] Page P. Sensorimotor training: a “global” approach for balance training. J Bodyw Mov Ther 2006;10:77–84.