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Effect of a 4-week elastic resistance band training regimen on back kinematics in horses trotting in-hand and on the lunge

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Summary

Background: Training and rehabilitation techniques aiming at improving core muscle strength may result in increased dynamic stability of the equine vertebral column. A system of elastic resistance bands is suggested to provide proprioceptive feedback during motion to encourage recruitment of core abdominal and hindquarter musculature for improved dynamic stability.
Objectives: To quantify the effects of a specific resistance band system on back kinematics during trot in-hand and lungeing at beginning and end of a 4-week exercise programme.
Study design: Quantitative analysis of back movement before/after a 4-week exercise programme.
Methods: Inertial sensor data were collected from seven horses at weeks 1 and 4 of an exercise protocol with elastic resistance bands. Translational (dorsoventral, mediolateral) and rotational (roll, pitch) range of motion of six landmarks from poll to coccygeal region were quantified during trot in-hand (hard surface) and during lungeing (soft surface, both reins) with/without elastic exercise bands. A mixed model ($P<0.05$) evaluated the effects of exercise bands, time (week) and movement direction (straight, left, right).
Results: The bands reduced roll, pitch and mediolateral displacement in the thoracolumbar region (all $P\leq0.04$). At week 4, independent of band usage, rotational movement (withers, thoracic) was reduced while dorsoventral movement (thoracic, coccygeal) increased. Increased back movement was measured in 80% of back movement parameters during lungeing.
Main limitations: Comparing each horse without and with bands without a control group does not distinguish whether the differences measured between weeks 1 and 4 are related to use of the bands, or only to the exercise regimen.
Conclusions: Results suggest that the elastic resistance bands reduce mediolateral and rotational movement of the thoracolumbar region (increase dynamic stability) in trot. Further studies should investigate the underlying mechanism with reference to core abdominal and hindquarter muscle recruitment and study the long-term effects.

The Summary is available in Chinese – see Supporting Information.

Keywords: horse; exercise; kinematics; training; elastic resistance band

Introduction

The vertebral column and its associated musculature is fundamental during locomotor activity to facilitate force transmission from the pelvic limbs through to the thoracic limbs, neck and head [1]. Due to this interdependency, altered gait patterns due to lameness or other pain stimuli (e.g. poor saddle fit [2]), can result in asymmetrical loading of the vertebral column. This can cause altered muscle activation patterns in both the locomotor and postural trunk muscles, which can then cause functional changes such as muscle spasm [3].

In order to rehabilitate affected muscle groups after veterinary intervention, the use of physical therapy techniques may be advocated. The evidence base of physical therapy for rehabilitation and performance development in horses and its relationship to clinical reasoning has been studied [4]. Protocols are specific to individual cases, but generally involve initial physical therapy/manipulation techniques, followed by a ground work programme which can incorporate the use of proprioceptive aids [5]. Recent work has shown an increased lumbosacral angle and dorsoventral displacement of the horse's back at trot on the lunge using the Pessoa training aid [6].

The Equiband[a] system (Fig 1) uses resistance band training to promote muscular rehabilitation and development in horses. The hindquarter band is intended to increase proprioception through stimulating a neuromuscular response, resulting in greater pelvic limb muscle activation [7]. The abdominal band fits around the middle third of the abdomen, with the intention of increasing recruitment of abdominal musculature during locomotion. Engagement of abdominal and hindquarter musculature is thought to encourage core postural muscle development and to improve dynamic stability of the back and pelvis, essential for ridden performance [6]. In people with poor muscular core strength, resistance band training has been shown to increase muscle activity of the pelvis and lower back [8–12]. In the present study we refer to increased 'dynamic stability' when a reduction in range of motion (either translational or rotational) is measured.

Spinal kinematics can be captured with optical motion capture systems, enabling accurate measurement of the small movements of the horse's back [13]. For in-field measurement of back movement, inertial measurement units (IMUs) are portable, validated [14], can identify breed specific back movement patterns [15] and be positioned under the saddle [16]. In trot, the range of movement varies between regions of the vertebral column [17,18]. Due to the vertically orientated articular surfaces and significant transverse vertebral processes in the lumbar region, there is minimal lateral bending or axial rotation in this region [19,20]. In comparison, flexion-extension and mediolateral displacement is greatest in the lumbosacral region [17,18] and may be related to the size and attachment of key muscle groups in this area. Pitch (or flexion-extension) movement is also maximal in this region due to the large joint space [19]. Dorsoventral displacement is greatest in the caudal thoracic region and range of motion is positively correlated with the distance from the body centre of mass (at the level of T13) [21,22].

We aimed to assess whether the use of a proprioceptive aid provided by an elastic resistance band resulted in differences in back kinematics in trot. Our objectives were to quantify back movement parameters indicative of

Fig 1: Picture of one of the horses enrolled in the study with the elastic resistance band system and inertial sensor system fitted.

dynamic stability without and with the use of elastic resistance bands before the start and at the end of a 4-week exercise regimen. We hypothesised that a reduced range of motion in the thoracolumbosacral region would be measurable at the trot with the bands.

Materials and methods

Horses

Seven privately owned general riding horses in regular (daily) exercise, (5 mares, 2 geldings, 4–22 years of age, 1.52–1.71 m withers height) were included (Supplementary Item 1). Each horse was considered by their owners as free from overt signs of back pain or lameness. Horses were training and competing at varying levels mainly for dressage. Data were collected at each horse's yard. Handler and site of data collection were consistent between gait assessments conducted at weeks 1 and 4.

Equipment

Each horse was fitted with its own bridle and a modified saddlepad[a] to which the elastic hindquarter and abdominal bands were attached using buckle clips. The bands were fitted at 30% tension (see Fig 1). Each handler was requested to check on a weekly basis that the tension was maintained at 30%. Band tension was checked by the person collecting the data at weeks 1 and 4 prior to data collection.

Eight MTx[b] IMUs were attached to the horse with custom-made neoprene pads using double-sided adhesive tape at poll (C1–2), withers (T5), 16th thoracic dorsal process (T16), lumbar area (L4-6), *os sacrum*, right and left *tuber coxae* and at the tail base (coccygeal area, 2 cm cranial to the tail head, at the level of Co 4–5). These sites were identified by palpation of skeletal landmarks by the same operator (V.S.) across horses.

The IMUs were placed in the same orientation (sensor x axis parallel to the sagittal axis of the horse) and attached to the wireless Xbus transmitter[b] which was mounted on a lunge roller. Data were transmitted at a sample rate of 100 Hz per individual channel (triaxial acceleration, maximum 18 ***g***, triaxial rate of turn, maximum 1200 deg/s and triaxial magnetic field, maximum 750 mGauss) to a wireless receiver connected to a laptop within receiving range (up to 100 m) running MT Manager[b] software.

Exercise and data collection regimen

Week 1: Day 1: Desensitisation of the horse to the resistance bands by gently rubbing them over the hindquarter and abdominal regions and under the tail. Walk and trot in-hand and lungeing with the hindquarter band at 10% tension. *Day 2*: Walk and trot in-hand and lunge with both abdominal and hindquarter bands at 10% tension. *Day 3*: Data collection without and with both bands at 30% tension (Fig 1). *Days 4–7*: Use of both bands in-hand/lunge at the start of each workout for 5 min. After removal of bands each horse's usual exercise regimen was followed.

Weeks 2–4: Both bands were used during ridden and lunge work at the start of the exercise session for 10 min (week 2, five times/week), 20 min (week 3, four times/week) and 30 min (week 4, three times/week), with emphasis on transitions in between and within gaits. On the days of band usage, each session time was shortened by one-third (week 3) or one half (week 4) of the normal work time. The reduction in sessions per week was implemented to compensate for the increase in exercise duration.

Week 4: Day 7: Data collection.

Data collection protocol

Inertial sensors were fitted to the horse and a minimum of 25 stride cycles of data were gathered [23] for each condition. Where the movement condition was not met (subjective observation of change in gait, accelerating, decelerating or stumbling), data collection was repeated. Data were obtained in-hand and on the lunge (not during ridden exercise) at trot at each horse's favoured speed, on a straight line (hard surface: asphalt or concrete) and on left and right reins on the lunge on an arena surface (approximately 20 m diameter circle):

1 Without bands, straight line
2 With bands, straight line
3 Without bands, left rein
4 Without bands, right rein
5 With bands, left rein
6 With bands, right rein

Kinematic analysis

Calculation of kinematic parameters was completed in MATLAB.[c]

Vertebral column 3D kinematics: A right-handed Cartesian coordinate system was used to calculate translational movement parameters from the inertial sensors with *x* craniocaudal, parallel to direction of motion, *z* dorsoventral, aligned with the gravitational field and *y* mediolateral, perpendicular to *x* and *z*. Rotational movements of roll (around the sensor x axis, the craniocaudal axis of horse or axial rotation) and pitch (around the sensor y axis, the mediolateral axis of horse or flexion-extension) were extracted from the sensors. Sensor displacements were calculated based on highpass filtering with frequencies of 1.5 Hz for integration from dorsoventral acceleration to displacement and of 0.75 Hz for integration from mediolateral acceleration to displacement [14]. After stride segmentation [24], four range of motion parameters were calculated per sensor and stride (translational: dorsoventral [DV] and mediolateral [ML] displacement; rotational: roll [R] and pitch [P]) as the difference between maximum and minimum value over a stride cycle. These parameters were calculated for the six sensors mounted along the midline of the horse from the poll to the base of the tail for the initial assessment without and with bands (week 1, Day 3) and for the final assessment without and with bands (week 4, Day 7).

Movement symmetry measures: Movement symmetry was calculated for the initial assessment without bands (week 1, Day 3) as an indicator of force distribution between contralateral limbs [25–27]. The symmetry parameters are based on vertical displacement of poll and pelvis (*os sacrum* sensor) and specifically were MinD, the difference between displacement minima during right fore (pelvis: left hind) and left fore (pelvis: right hind) stance and MaxD, the difference between displacement maxima after right fore (pelvis: left hind) and left fore (pelvis: right hind) stance [28]. The difference between left and right *tuber coxae* upward movement (hip hike difference, HHD) was calculated [29]. All symmetry parameters were expressed in mm (zero indicating perfect symmetry). For head (pelvic) movement, positive MinD indicates a higher position of the

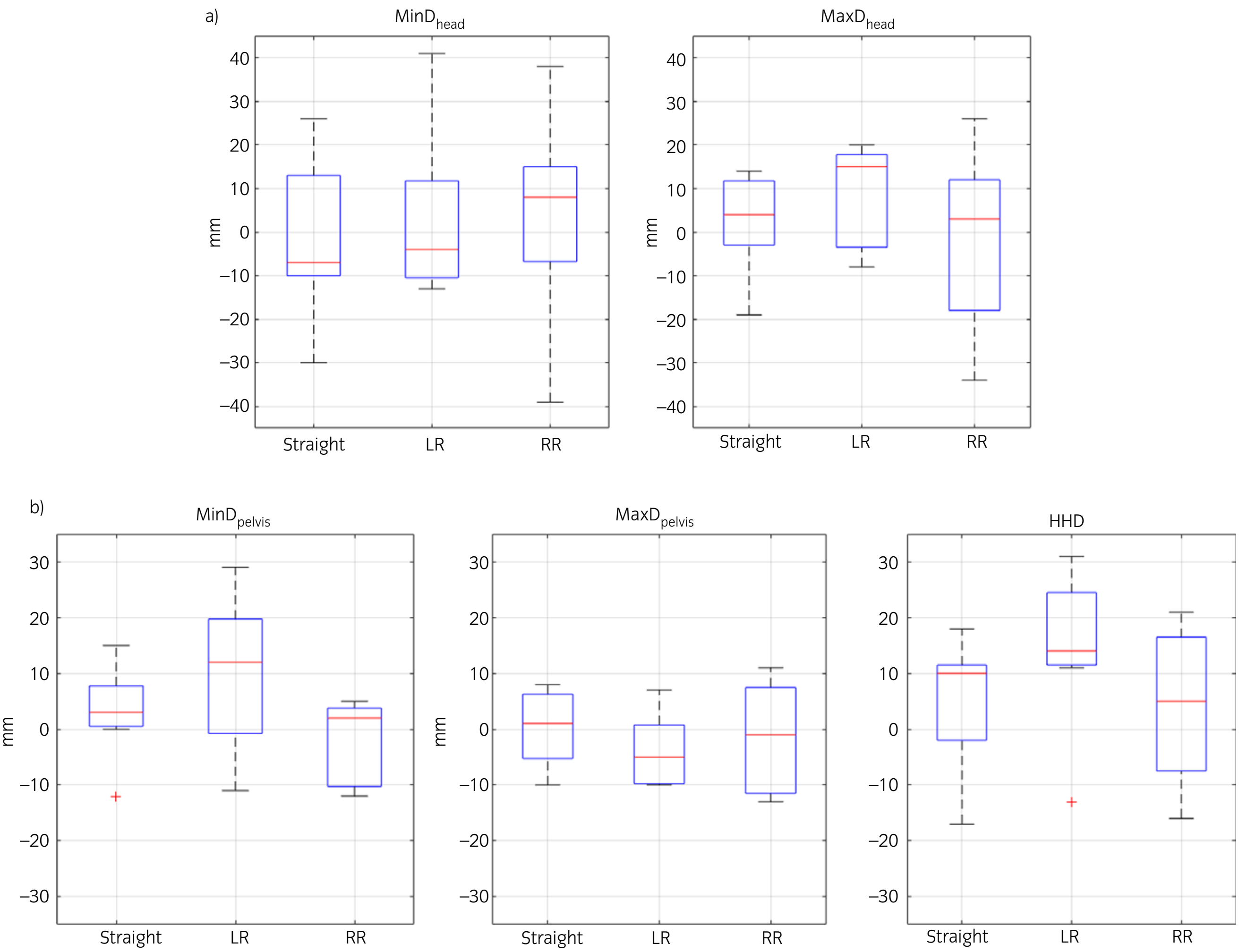

Fig 2: a) Head and b) pelvic movement symmetry values of n = 7 horses for trot in-hand on hard surface (straight) and on the lunge (soft surface) on left and right rein (LR, RR). Movement symmetry values generally (with the exception of pelvic MinD, the difference between vertical pelvic displacement minima during left and right hindlimb stance) include zero (value for perfect symmetry) and show considerable variation between horses. Median values indicate a lower position of the head during RF stance (negative HDmin) on the straight line and left rein and a lower head position during LF stance (positive $MinD_{head}$) on the right rein. $MinD_{head}$ indicates a higher position of the head after RF stance for all three conditions. Median pelvic movement asymmetry shows a higher position of the pelvis during LH stance ($MinD_{pelvis}$), most exacerbated on the left rein. $MaxD_{pelvis}$ shows near zero median values (near symmetrical movement) on the straight and right rein and indicates increased pelvis position after RH stance on the left rein. HHD is positive throughout indicating increased movement amplitude of the left *tuber coxae* compared with the right, most pronounced on the left rein.

head during RF stance (of the pelvis during LH stance) and a positive MaxD indicates a higher position of the head after RF stance (of the pelvis after LH stance).

Stride time: As part of the stride segmentation procedure, stride time (in ms) was extracted for each identified stride. Average stride time values for each horse for each exercise condition were calculated.

Data analysis: A mixed linear model was implemented in SPSS,[d] with level of significance of P<0.05 and translational and rotational range of motion as dependent parameters, horse as a random factor and band condition (with or without), direction (straight, left rein, right rein) and time (week 1, week 4) as fixed factors and stride time as a covariate. The three main effects, as well as all three possible two-way interactions and the three-way interaction between band condition, direction and time were assessed. Within each horse, stride time varied from its subject mean by on average ±5% (±3.8% to ±7% across horses). As a result, stride time was entered linearly into the model.

Model residual histograms were inspected visually for outliers. Estimated marginal means of factors with P<0.05 were inspected and post-hoc tests were carried out (Bonferroni), to establish pairwise significant differences for factors with more than two categories (i.e. direction with P value of 0.05/3).

Results

In total, range of motion data were calculated from 3215 strides of seven horses assessed at two time points (week 1, week 4), for two band conditions (without, with) and three movement direction (straight, left rein, right rein). Mean values for each horse for each of the 12 conditions were calculated from an average of 38.3 strides (between 25 and 89 strides per condition). These mean values were used for statistical analysis.

Stride time was on average across all conditions 739 ms (median: 737.5 ms, range: 660–818 ms). On the straight, average stride time was 724 ms (median: 728.5 ms) compared with 749 ms (744.5 ms) on the left rein and 745 ms (739.5 ms) on the right rein. Average stride time for assessment without exercise bands was 740 ms (738.5 ms) and with the bands 738 ms (737.5 ms). At week 1, stride time was found to be 732 ms (732 ms) and 746 ms (752 ms) at week 4.

Movement symmetry

Movement symmetry parameters for head (MinD, MaxD) and pelvis (MinD, MaxD, HHD) for the horses during the initial data collection session before application of the exercise bands are summarised in Figure 2. With the exception of pelvic MinD, interquartile ranges (boxes) for the symmetry values recorded during in-hand (straight line) trot include zero (perfect symmetry) with considerable spread seen across the seven horses.

Back kinematic parameters

Grand means across all three conditions (band, direction and time) are illustrated in Figure 3 showing an increase in DV range of motion from the poll to the mid-thoracic region and a decrease caudal to the mid-thoracic region with values ranging between 72 mm (poll and coccygeal) and 97 mm (thoracic). In contrast, ML range of motion decreased from the poll to the withers and then increased caudal to the withers with values ranging from 26 mm (withers) to 51 mm (coccygeal). Roll increased from the poll (6.7°) to the *os sacrum* (20.9°) and decreased to 13.3° caudal to the *os sacrum*. Pitch showed comparatively little variation between anatomical sites with the smallest values found for withers (5.4°) and the mid-thoracic region (5.5°) and the highest values for the poll (7.7°) and the *os sacrum* (7.2°).

Effect of band, direction and time

An overview of the statistical significance for the three main effects (band, direction, time) and their interaction can be found in Supplementary Item 2. Below we describe the significant changes observed as a result of the mixed linear model.

Band condition: Range of motion of withers roll was 1.5° smaller (P<0.0001) in horses with the bands (9.3°) compared to without the bands (10.8°). Withers pitch range of motion was 0.3° smaller (P = 0.036) when trotting with the bands (5.3°) compared to without (5.6°). Mediolateral movement in the mid-thoracic region was 2.3 mm reduced (P = 0.016) in horses with the bands (28.2 mm) compared with horses without the bands (30.5 mm) and mediolateral movement in the lumbar region was also smaller (by 7 mm, P<0.0001) with the bands (31.1 mm) compared to without the bands (38.1 mm). See Figure 4 for box plots comparing between without and with band usage for the parameters showing significant changes.

Time: Differences between weeks were found for roll of withers (P = 0.004) and of T16 (P = 0.03), pitch of the lumbar region (P = 0.019) and dorsoventral movement of T16 (P = 0.02) and coccygeal region (P = 0.031). From weeks 1–4, roll showed a decrease of 1° (withers) and 0.8° (thoracic), pitch in the lumbar region decreased by 1.4° and dorsoventral movement increased by 1.7 mm (thoracic) and 2.5 mm (coccygeal).

Direction: A total of 79% (19/24) of back kinematic parameters showed a significant effect for direction (Table 1 and Supplementary Item 2). The majority showed significant differences between straight line and left rein and between straight line and right rein. Two of the parameters (mediolateral poll range of motion and coccygeal pitch) additionally showed differences between left and right rein while three parameters only showed differences between straight line and one of the reins (dorsoventral withers and pelvis range of motion and lumbar roll range of motion). All values were greater on the lunge compared with straight line movement. Average change between straight line and lungeing (average of left and right rein) of 10% increase was measured for dorsoventral movement (for six sensors), 24% increase for mediolateral movement (for six sensors), 16% increase for roll (for four sensors) and 23% increase for pitch (for three sensors).

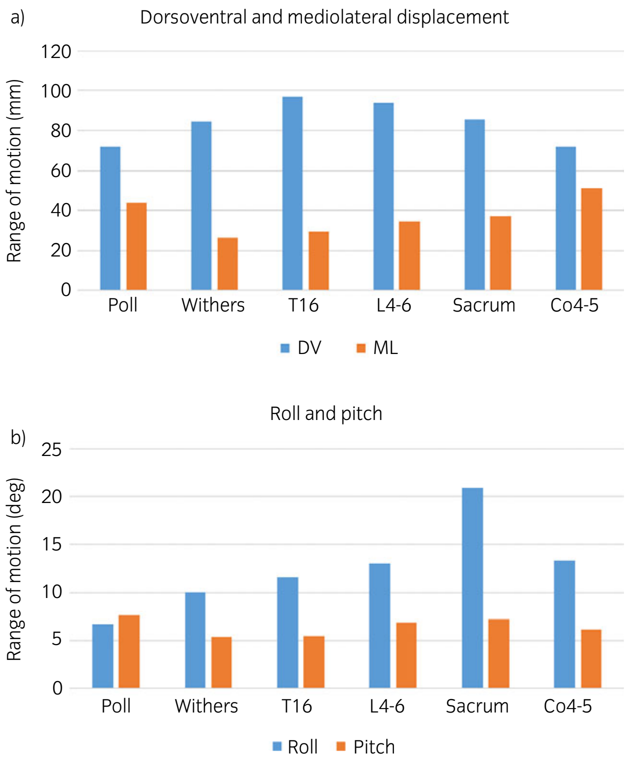

Fig 3: Dorsoventral and mediolateral a) and roll and pitch b) range of motion of the seven study horses averaged across all 12 conditions (without/with band, direction [straight, left rein, right rein] and time [week 1/week 4]). Presented are grand means extracted from the mixed model with horse as random factor, movement direction, band usage and time as fixed factors and stride time as covariate and range of motion parameters as outcome variables.

Discussion

We quantified the effects of a specific system of elastic resistance bands (Equiband) on back kinematic parameters in seven riding horses over a 4-week period. The resistance bands significantly reduced withers roll and pitch and thoracic and lumbar mediolateral movement, providing support for our hypothesis that this proprioceptive aid improves dynamic stability of the vertebral column in trot in-hand and on the lunge. The effects appeared to be concentrated on the thoracolumbar area and no differences were found caudal to the *os sacrum*. Whether the changes are related to the stimulation of hindquarter and abdominal muscle recruitment, resulting in increased activation of the postural core muscles, cannot be answered by this study. This requires direct measurement of muscle activity of muscles such as the *multifidus* and *iliopsoas,* which are thought to help with limiting energy losses through decreasing lateral excursion of the vertebral column [30]. It should be acknowledged that decreased thoracolumbar pitch (flexion-extension) can be seen in older horses and those exhibiting signs of back pain [19,31]. When asked informally, the riders in this study felt greater 'stability of movement' with the resistance band system. Ridden exercise was part of the exercise regimen, but no gait analysis data were obtained for this condition. Further investigation is warranted to quantify the effects of use of resistance bands on back kinematics during ridden exercise.

In comparison to the Pessoa training aid (PTA) [6], the resistance bands did not have a direct effect on lumbosacral flexion (pitch) or overall dorsoventral displacement. Dorsoventral displacement was increased at week 4 however independent of band usage. Whether or not this indicates an effect of the band usage over 4 weeks allowing the horses to push off into the air more efficiently needs to be addressed by future studies. We used a range of horses of different breed and age. Published in vitro work found that around one-third of horses have anatomical variations in the lumbosacral area which may impact on maximal dorsoventral displacement [32]; however, presence of anatomical variations was not assessed here. In comparison to attachments of the PTA, the EquiBand system does not have a direct connection with the horse's mouth and hence avoids the oral desensitisation effects seen with incorrect use of the PTA [33] when using

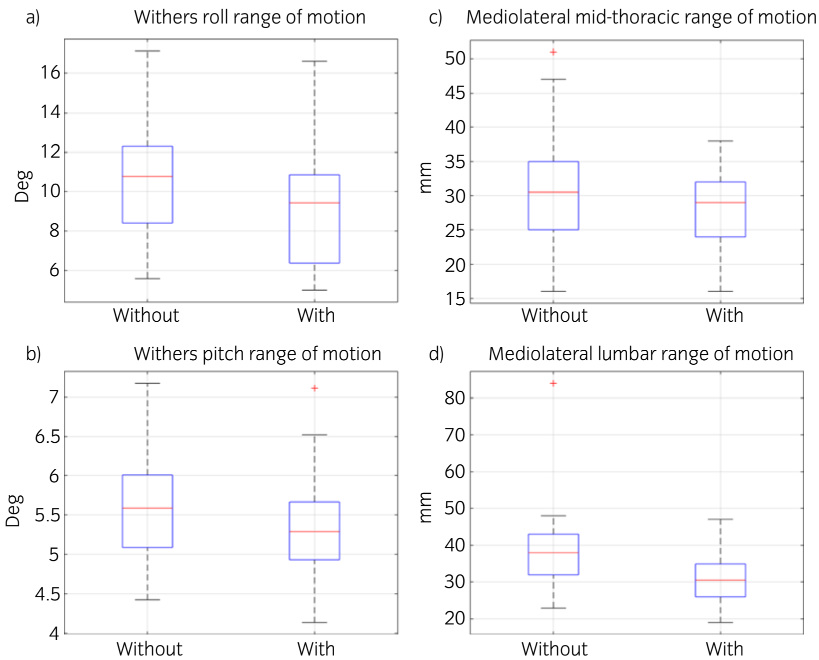

Fig 4: Box plots illustrating the effect of the band system (the four parameters showing significant differences without/with band usage in the mixed model) on range of motion of withers pitch a) and withers roll b), of mediolateral range of motion of the mid-thoracic c) and lumbar regions d). Shown are average values for significant changes between band conditions from n = 7 horses measured across two time points and during straightline trot and while trotting on the lunge (n = 42 values per box). All four significant changes result in a reduced range of motion (increased dynamic stability) with the use of the bands.

the EquiBand system during lungeing. The system can of course also be used during ridden exercise.

We assessed horses in-hand and on the lunge. A high proportion of parameters across all regions showed increased ranges of motion on the lunge compared with straight line trot. Previous studies on lungeing have mainly focused on movement symmetry and limb angles of horses on the lunge [34–38], providing little scope for comparison. However, the increased ranges of motion are likely, independent of band usage, related to the additional production of centripetal force of locomotion on a curve, resulting in an increase in total force [39] and increased peak forces measured in the outside front limb [40]. As demonstrated with the PTA [6] on the lunge, the greater dorsoventral displacement and lumbosacral flexion (pitch) may be related to increased activation of core postural muscles.

Only five differences in movement parameters were measured between weeks. Three of these were related to rotational range of motion and each showed a decrease from weeks 1 to 4. The two remaining parameters, thoracic and coccygeal, were related to dorsoventral range of motion, which increased from weeks 1 to 4. This is a movement direction that was not influenced by the resistance bands. The statistical model did not identify an interaction between use of the exercise bands and time. The study design, comparing each horse without and with bands, does not distinguish whether the differences between weeks 1 and 4 are related to use of the bands, or only to the exercise regimen. This would require a control group of horses undergoing the same exercises but without the use of the exercise bands. A reduction in rotational movement of the thoracolumbar area may be beneficial when considering the support required to carry a saddle and rider [41] and may also be what the riders are referring to when subjectively reporting ‘more stability’.

Although not the focus of this study, we assessed movement symmetry of the head and pelvis at the first data collection. The recorded values are an indicator of symmetry between left and right fore- and hindlimbs with respect to weightbearing and push-off [25]. All horses had been judged as being ‘fit to perform’ at their respective level of training. In agreement with studies based on visual assessment [42] or quantitative gait analysis [43,44], based on our IMU data not all seven horses would have been classified as within normal limits (±7.5 mm for head and ±4 mm for pelvic movement, thresholds from [45] adapted using the equations presented in [46]). Without any clinical diagnostics, it is impossible to conclude how many horses would be classified as lame by a veterinarian. It would also be of interest to evaluate the effect of elastic resistance bands in the presence of hindlimb lameness, since compensatory force distribution from the hindlimbs to the front limbs may be influenced by proprioceptive feedback from the hindquarters and by increased dynamic stability allowing more efficient transfer of force from the affected hindlimb to the compensatory front limb [47].

We implemented a field study using privately owned horses over a period of time. Variability of rider influence [48,49] during the completion of the 4 weeks exercise protocol, as well as protocol compliance could not be controlled. Variables such as the person placing the sensors and operating the equipment (V.S.), the person handling the horses and the surface used during gait assessment were kept constant for each horse. It was more challenging to control circle diameter and speed of motion, which are known to affect movement symmetry and kinematics [36–38]. Horse height and conformation also influence back movement [19] with taller horses possessing longer thoracic regions and exhibiting greater lateral bending in the lumbar region. However, this study design emphasised comparisons within each horse between exercise with and without use of bands and over time. We chose not to randomise the order of assessment (always without bands first) for each condition, since it is unknown whether there is a carryover effect affecting movement parameters even after removal of the bands. To minimise the risk of a carryover effect influencing our results, horses were moved in walk after removal of the bands. The existence of a carryover effect should be investigated further in future studies with a series of repeat assessments after removal of the bands.

Conclusion and future work

This study provides quantitative evidence to suggest that use of a specific elastic exercise band system (Equiband) as part of an exercise protocol, increases dynamic stability of the thoracolumbar area in the trotting horse in-hand and on the lunge. The study design did not allow a judgement of

TABLE 1: Results of the mixed model analysis with regards to trot 'direction' comparing translational and rotational ranges of motion between straight line, in-hand trot (S, straight line) and trot on the lunge on left (L) and right (R) rein from seven horses

Anatomical landmark	Kinematic parameter	P value	Post-hoc test result
Poll	DVROM	**<0.0001**	S^2L, S^2R
	MLROM	**<0.0001**	S^2L, S^2R, L^2R
	RROM	**<0.0001**	S^2L, S^2R
	PROM	0.201	
Withers	DVROM	**0.007**	S^2R
	MLROM	**<0.0001**	S^2L, S^2R
	RROM	0.179	
	PROM	0.157	
T16	DVROM	**<0.0001**	S^2L, S^2R
	MLROM	**<0.0001**	S^2L, S^2R
	RROM	0.217	
	PROM	**0.005**	S^2L, S^2R
L4–6	DVROM	**<0.0001**	S^2L, S^2R
	MLROM	**<0.0001**	S^2L, S^2R
	RROM	**0.029**	S^2L
	PROM	0.183	
Sacrum	DVROM	**0.024**	S^2L
	MLROM	**<0.0001**	S^2L, S^2R
	RROM	**<0.0001**	S^2L, S^2R
	PROM	**0.001**	S^2L, S^2R
Co4–5	DVROM	**<0.0001**	S^2L, S^2R
	MLROM	**<0.0001**	S^2L, S^2R
	RROM	**0.006**	S^2L, S^2R
	PROM	**<0.0001**	S^2L, S^2R, L^2R

P-values <0.05 in bold.
Co4–5, coccygeal vertebrae 4-5; DV, dorsoventral; ML, mediolateral; R, roll; P, pitch; ROM, ranges of motion. P values (after Bonferroni correction) are given as well as significant pairwise comparisons with S^2L indicating a difference between S and L; S^2R, a difference between S and R; L^2R, a difference between L and R.

whether the exercise regimen alone (without the band system) would have similar effects. Further studies should identify whether the effect of the band system is due to increased activation of the deep core musculature related to dynamic spinal stability.

Authors' declaration of interests

N.C. Stubbs and N. Rombach developed the Equiband system and advised on its correct use. Neither of them was involved in data collection or processing.

Ethical animal research

This study was authorised by the Royal Veterinary College Ethics and Welfare Committee (URN 2013 1238). Owners gave informed consent for inclusion of their horses.

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Authorship

The study was designed by all authors. V. Simons executed data collection. V. Simons and T. Pfau performed data processing. All authors were involved in data interpretation, preparation of the manuscript and gave their final approval.

Manufacturers' addresses

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[b]Xsens, Enschede, The Netherlands.
[c]The Mathworks Inc., Natick, Massachusetts, USA.
[d]SPSS Inc., Chicago, Illinois, USA.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Summary in Chinese.

Supplementary Item 1: Horse details.

Supplementary Item 2: Mixed model analysis for range of motion parameters.