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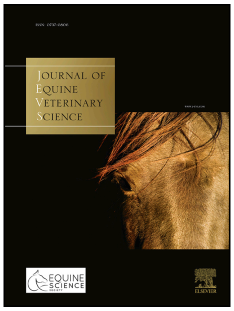

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The Effect of Tungsten Road Nails on Upper Body Movement Asymmetry in Horses Trotting on Tarmac

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Competing Interests

We have the following interests: PD is a registered farrier, LC is a registered farrier and TP is owner of EquiGait, a provider of gait analysis products and services. This does not alter our adherence to all policies on sharing data and materials.

Abstract

Reason for study: Tungsten road nails are commonly used by farriers to increase grip between the hoof and the ground surface. There is limited evidence relating the use of road nails to the fundamental mechanics of movement. Grip is important for efficient deceleration on landing and subsequent propulsion, but this must be balanced against an amount of slip to divide the landing force into horizontal as well as vertical subcomponents. *Objective*: To quantify the effect of lateral heel road nail placement on weight bearing and propulsion in horses trotting on tarmac. *Method*: In this intervention study, wireless inertial measurement units measured vertical movement asymmetry in 10 horses. Differences in head and pelvic movement asymmetry before/after subsequent application of laterally placed road nails to forelimb and hindlimb hooves in a randomised order were compared to zero value (no change) with a one-sample t-test, P<0.05. *Results*: Left-to-right tuber coxae movement amplitude difference was significantly more negative (-3.25 mm, P=0.03), suggesting more right than left tuber coxae movement amplitude, after application of a road nail to the left hindlimb. No movement asymmetries at the poll, withers or sacrum were detected following nail placement (all P>0.055). *Conclusion:* Pelvic movement indicates a very small increase in weight bearing and propulsion provided by the hindlimb with a laterally placed road nail compared to the contralateral hindlimb. Further work is needed to investigate slip and grip related parameters at the level of the hoof and to investigate the long-term consequences of very small changes in movement asymmetry.

Keywords

Equine, biomechanics, trotting, road nail, tarmac, gait analysis, movement symmetry

1. Introduction

Horseshoes operate at the interface between horses' hooves and the surfaces they are moving over. Modulating fundamental characteristics of the hoof-surface interface, such as friction, traction, shock damping or the parameters of the propulsive effort [1] can be achieved in two ways: 1) adapting surface characteristics; or 2) modifying the shoeing regime. The first approach is efficient for managing sports and racehorses that regularly work on surfaces specifically dedicated to equestrian activities. Considerable research efforts have been implemented to this effect in recent years (e.g. [2–7]) and it is important to relate the objectively measurable characteristics to the subjective assessment of expert riders [2]. In contrast, adapting multi-user surfaces, such as roads, to horse specific requirements is difficult to justify if this compromises the safety or efficiency of other users, such as motor vehicles. In this case, it may be more appropriate to alter a horse's shoes to achieve the required shoe-surface interaction. Horseshoes serve the additional purpose of protecting the hooves against excessive wear on these surfaces [8].

It is apparent that hard surfaces have different characteristics to other equestrian footings: for example, Barstow et al. [9] identified higher hoof impact shock related frequencies and powers on road surfaces compared to grass and gravel. Reduced frequencies and amplitudes proximal to the fetlock joint indicate that the equine limb is efficient at damping impact shock waves [10]. The initial braking time, during which the hoof may experience some degree of horizontal slip, occurs at the beginning of the stance phase and has been identified as an important parameter in the damping process, with a shorter time associated with more rapid oscillations [10]. The association between slip time and distance can be manipulated by using different shoeing materials and/or traction devices that affect horizontal (braking) and vertical force production [11–13]. Tungsten road nails may be fixed to the shoes of horses exercising on roads to help reduce excessive slippage at foot contact [14]; a similar approach to the use of studs on grass surfaces [15]. It is also plausible that the use of road nails is related to changes in force production, similar to the changes seen as a function of different shoeing materials [12,13].

Upper body movement asymmetries can be quantified using inertial measurement units (IMUs). In lame horses, these displacement asymmetries (mm-scale) have been associated with asymmetries in vertical and horizontal force production [16–18]. Hence, by quantifying upper body movement asymmetries, it is possible to identify whether an asymmetrical intervention, i.e. an intervention applied to one side (or one limb) of the horse only, will lead to an asymmetrical force production. Here, we hypothesize that applying a road nail to the shoe of one limb will initiate upper body movement asymmetries indicative of increased vertical force production with that limb compared to the contralateral limb; by reducing slip through the use of a road nail, the horse would then be able to produce vertical force more efficiently.

2. Materials and Methods

Ethical approval for this intervention study was granted by the Ethics and Welfare committee at the authors' institution (URN: M2017 0120). Informed consent was given by the owners of the horses participating in this study.

2.1 Data collection

Ten horses that ranged in height at the withers from 1.52 m to 1.70 m and that were in regular work and not considered lame by their owners were included in the study. Wireless MTw (Xsens, The Netherlands) IMUs were fitted to the poll, withers, sacrum and left and right tuber coxae of each horse. Data collection for each shoeing condition was conducted with the horses trotting in-hand in a straight line over tarmac surfaces for a minimum of 25 strides. The tarmac was dry and free from surface debris, and the ambient temperature fell between 18 and 20°C. Data were transmitted wirelessly at an update rate of 60 Hz to a nearby computer running dedicated data collection (MTManager 4.8, Xsens, The Netherlands) and data processing (MATLAB R2015b) software. Data from different horses were collected on different days at four equestrian locations across Hertfordshire. At the time of data collection, each horse was at the end of its shoeing cycle: between five and six weeks after the previous shoeing. All horses had their symmetry assessed before the insertion of any road nails to ensure that any subsequent differences after road nail emplacement could be attributable to the nail and not a consequence of inherent laterality or asymmetrical gait patterns. Road nails were fitted into the last nail hole of the lateral heel of the horses' shoe(s) on one side; the effect of forelimb and hindlimbs nails were assessed both independently and collectively in a randomised order. For this asymmetrical intervention study, horses were randomly allocated to one of two groups: group 1 had road nails fitted to the left fore- and/or hindlimb; group 2 had road nails fitted to the right fore- and/or hindlimb. Movement asymmetry parameters for each horse and each condition were then calculated as median values over all stride cycles under each of the following conditions:

1. Baseline condition without road nails.
2. With road nail used in either one front or one hind shoe.
3. With road nail used in both front and hind shoe in ipsilateral limbs.

The time taken to insert nails and reset the gait analysis system (8–10 minutes) was used as the washout period between trials.

2.2 Data Processing

Continuous data streams were first integrated to vertical displacement based on each IMU's orientation and tri-axial acceleration data [19] and then segmented into strides following published protocols [20]. The IMU based approach adopted here works by quantifying the differences in movement between two halves of a trot stride as a function of each intervention. Therefore, the interventions outlined (*section 2.1*) were deliberately 'one-sided', i.e. road nail applied to only the left or right leg, so any movement asymmetry resulting from small increases or decreases in force during both stance phases could be detected. Movement asymmetry would be unaffected if the force were to be changed equally in both limbs.

For each stride cycle, 10 movement asymmetry parameters were calculated: three each for the head, withers and sacrum mounted IMUs, and one parameter for comparing vertical displacement between left to right tuber coxae [18]. The difference between the two minima, maxima or upward movement amplitudes measured in the two halves of each stride for the head (H), withers (W) and pelvis (P) were quantified as: HDmin, HDmax and HDup; WDmin, WDmax and WDup; and PDmin, PDmax and PDup, respectively. Hip hike difference (HHD) was calculated as the difference between the left tuber coxae amplitude during right hind stance and the right tuber coxae amplitude during left hind stance. To allow a straightforward combination of data from horses in group 1 (road nails applied to left limbs, N=6, Table 1) and group 2 (road nails applied to right limbs, N=4, Table 1), the movement asymmetry values of horses in group 2 were inverted (their data multiplied by -1) so we effectively measured the mirror image of these horses.

2.3 Statistical testing

Histograms were used to assess for normality. The resulting data from 'before' and 'after' the 1-sided interventions for the different horses were tested for significant differences using one-sample t-tests ($P<0.05$) performed using SPSS statistical software. These tests compared the differences in movement asymmetry parameters before/after application of road nails to a value of zero, i.e. a hypothesized value representing 'no change' between the condition before and the condition after the use of road nails. It is necessary to study differences in movement asymmetry between the 'baseline' and different interventions to remove the masking effect of horses that start from different 'starting points' along the movement asymmetry scale. Therefore, a horse's 'baseline' asymmetry may be 'left' or 'right' sided, and hence create negative or positive values, but if it has a 'before-after' difference of zero then the output of a one-sample t-test test will indicate that the road nail intervention has had no effect on movement asymmetry, or the underlying force asymmetry.

For forelimb related movement asymmetry parameters (HDmin, HDmax, HDup, WDmin, WDmax, WDup), differences between the condition before and after the application of the forelimb road nail were calculated. Differences between the baseline condition and each instance of applying a road nail to the front limb were also calculated. For hindlimb related movement asymmetry parameters (PDmin, PDmax, PDup, HHD), differences between the condition before and after each instance of applying a road nail to a hindlimb were calculated. Differences between the baseline condition and each instance of applying a road nail to the hindlimb were also calculated.

In the one-sample t-test, all data for the hindlimb conditions (hindlimb nail only and forelimb and hindlimb nails) or forelimb conditions (forelimb nail only and forelimb and hindlimb nails) were considered together when evaluating the effect of a hindlimb or forelimb nail for two reasons. First, the repeated-limb measurements from the same horse originate from two different experimental scenarios. Second, previous studies have shown small 'compensatory' changes in movement asymmetry from the front to hind or vice versa [21].

3. Results

3.1 Baseline Movement Asymmetry Values

Movement asymmetry values for the head, withers and pelvis of all horses and descriptive statistics can be found in table 1 for the baseline condition, i.e. before application of any road nails. Average asymmetry values are generally small; ranging from -3.4 mm to +4.6 mm. Variation across horses is considerable with the most negative baseline asymmetry value found as -31 mm and the most positive baseline asymmetry value as +20 mm. This results in mean absolute values (meanabs, table 1), i.e. eliminating the direction of asymmetry before calculating a mean, that range between 5 mm and 12 mm.

Table 1: Movement asymmetry values for all horses for the head (H), withers (W), mid-pelvis (P) and tuber coxae (HHD) at trot in the baseline condition (before any application of road nails).

Horse ID	Side of intervention	# strides	Stride time (ms)	HDmin	HDmax	HDup	WDmin	WDmax	WDup	PDmin	PDmax	PDup	HHD
1	L	25	783	-5	3	-4	-7	-10	-14	2	5	7	12
2	L	25	749	7	7	13	9	2	11	-6	6	-1	-1
3	R	28	670	10	7	17	9	9	17	-9	-8	-17	-22
4	L	25	723	-7	0	-8	-1	3	1	-8	-1	-9	-7
5	L	33	650	17	-9	10	-3	1	-2	8	-1	6	10
6	R	25	734	6	-10	-5	-4	-1	-3	-1	5	4	12
7	R	25	792	15	4	20	4	-7	-5	-12	8	-6	-13
8	L	27	727	5	-6	1	-1	-3	-5	2	13	17	18
9	R	29	693	-31	11	-16	-11	-9	-21	4	8	14	12
10	L	32	670	-18	-2	-17	-7	-6	-13	-5	11	8	7

Mean	**27**	**719**	**-0.1**	**0.5**	**1.1**	**-1.2**	**-2.1**	**-3.4**	**-2.5**	**4.6**	**2.3**	**2.8**
Std	**3**	**48**	**15.2**	**7.2**	**13.3**	**6.7**	**6.0**	**11.4**	**6.5**	**6.3**	**10.6**	**13.0**
Min	**25**	**650**	**-31**	**-10**	**-17**	**-11**	**-10**	**-21**	**-12**	**-8**	**-17**	**-22**
Max	**33**	**792**	**17**	**11**	**20**	**9**	**9**	**17**	**8**	**13**	**17**	**18**
Meanabs	NA	NA	**12.1**	**5.9**	**11.1**	**5.6**	**5.1**	**9.2**	**5.7**	**6.6**	**8.9**	**11.4**
Stdabs	NA	NA	**8.3**	**3.6**	**6.5**	**3.5**	**3.5**	**6.9**	**3.6**	**3.9**	**5.4**	**5.9**

3.2 Effect of Road Nails

None of the forelimb related asymmetry variables (HDmin, HDmax, HDup, WDmin, WDmax, WDup) showed a significant difference before/after the application of a road nail in the forelimb. Mean absolute differences before/after road nail application ranged from -0.3 mm for WDmin to 4.1 mm for HDup with standard deviations between 3.4 mm (WDmin) and 8.8 mm (HDup); see Table 2 for details.

Table 2: Sample size, descriptive statistics and p-values for a one-sample t-test for difference before/after the application of a forelimb road nail. Listed are forelimb asymmetry related parameters describing head (HDmin, HDmax, HDup) and withers (WDmin, WDmax, WDup) movement asymmetries.

Variable	**N**	**Mean (mm)**	**Std (mm)**	**Stderr (mm)**	**Sig.**
HDmin	20	3.4	7.6	1.7	0.061
HDmax	20	0.9	4.0	0.9	0.353
HDup	20	4.1	8.8	2.0	0.055
WDmin	20	-0.3	3.4	0.8	0.694
WDmax	20	1.5	4.1	0.9	0.132
WDup	20	0.2	4.1	0.9	0.872

After application of a road nail to the left hindlimb, HHD showed a significant difference of -3.3 mm (P=0.031) (Figure 1). The negative sign indicates a type of pelvic movement asymmetry pattern typically seen in right hindlimb lame horses, i.e. horses showing reduced force production with the right hindlimb; in this case, the limb without the road nail. Mean differences before/after road nail application had the largest absolute value of -3.3 mm for HHD and the smallest absolute value of -0.7 mm for PDmax. Standard deviations of before/after differences ranged from 2.9 mm for PDmin to 6.2 mm for HHD; see Table 3 for details. PDmin, PDmax and PDup showed no significant differences before/after the application of road nails.

Table 3: Sample size, descriptive statistics and p-values of a one-sample t-test for difference before/after application of hindlimb road nail. Hindlimb asymmetry related parameters describing mid-pelvic (PDmin, PDmax, PDup) and tuber coxae (HHD) related asymmetry are listed.

Variable	**N**	**Mean (mm)**	**Std (mm)**	**Stderr (mm)**	**Sig.**
PDmin	20	-1.2	2.9	0.7	0.093
PDmax	20	-0.7	3.6	0.8	0.392
PDup	20	-1.6	5.6	1.3	0.219
HHD	20	**-3.3**	**6.2**	**1.4**	**0.031**

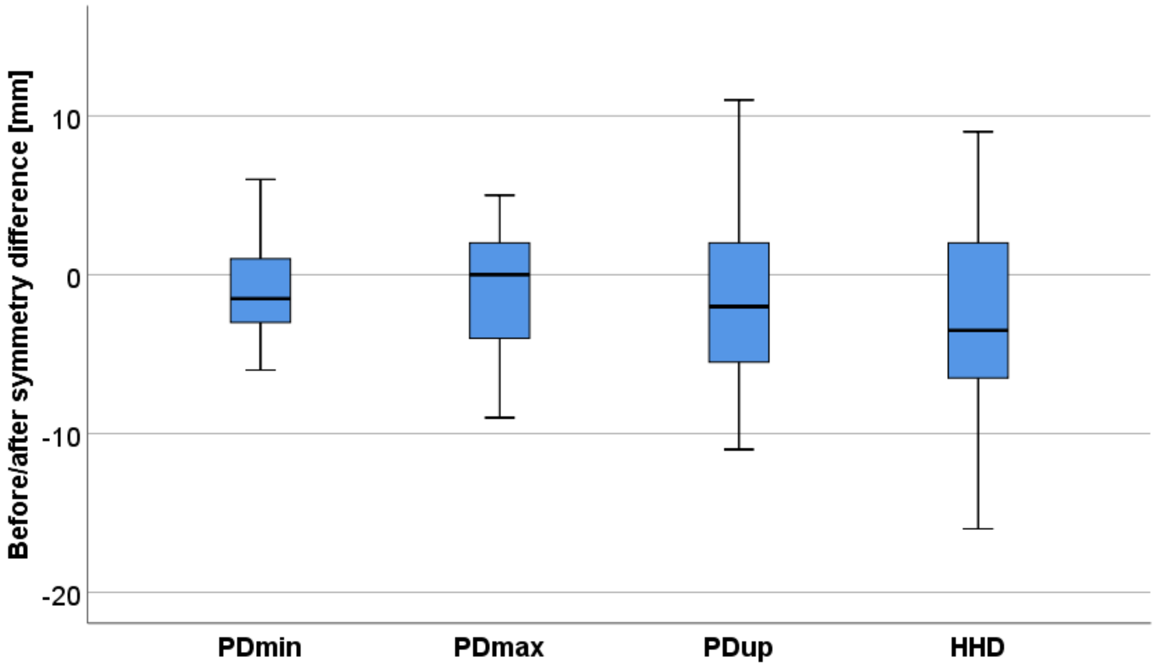

Figure 1: Boxplot showing the before/after difference for hindlimb related asymmetry parameters (PDmin, PDmax, PDup, HHD) for application of a hindlimb road nail. Each box contains 2 samples from each of the ten horses, i.e. N=20 samples for each box. Boxes are the 25th and 75th percentile, line within box is the median, T-bars extend to minimum and maximum values.

4. Discussion

This study set out to investigate the effect of laterally placed road nails on upper body movement asymmetry of horses trotting in-hand on tarmac surfaces. It has long been considered a necessity to use traction devices within the shoe to reduce excessive slip and establish grip on hard surfaces [12], such as tarmac roads, and their use is intended to promote stability of the foot whilst in contact with the ground. Small but significant changes in pelvic movement asymmetry could be identified in our study in relation to the use of a road nail in a hindlimb shoe. This supports the hypothesis that road nails can alter upper body movement by influencing vertical force production during trot on tarmac.

However, no significant changes to head or withers movement were found as a function of road nail placement in one of the forelimb shoes.

It is worth noting that the changes in average pelvic movement asymmetry patterns observed when adding a road nail to a hindlimb (Table 3) generated before/after difference values that were negative across all four parameters, although the only negative value that was statistically significantly different from zero was measured for HHD. The HHD parameter describes the movement of the pelvis by comparing left and right tuber coxae movement amplitudes. The identified difference in HHD indicates that the movement amplitude of the right tuber coxae (the side without the road nail) is mildly higher than the movement amplitude of the left tuber coxae (the side with the added road nail). This pattern is consistent with that observed in horses with mild right hindlimb lameness [22]. Although alterations to the movement of the hindquarters can be reflected in compensatory movements at the withers and poll [23,24], the small displacement amplitudes recorded at the pelvis here, combined with high head movement variability, mean that any such effect, if present, falls below our detection limits.

It has been shown that horses with hindlimb lameness produce less force and impulse with the affected (lame) limb [17,25]. The typical midline pelvic movement patterns, i.e. movement of the sacrum, here PDmin, PDmax and PDup, in hindlimb lame horses show associations between reduced peak force at mid stance and PDmin, and associations between the transfer of vertical to horizontal ground reaction force impulse in the second half of stance (reduced "pushoff") and PDmax [17]. Pushoff reflects the amount of upward pushing in the second half of stance and can be quantified as the difference between the minimum vertical position at mid stance and the maximum vertical position after the stance phase. The negative value for PDmin here is consistent with a non-significantly reduced peak force with the right hindlimb, i.e. higher peak force with the limb with the road nail compared to the contralateral limb. The negative values for PDmax and PDup on the other hand would be indicative of a non-significantly reduced pushoff with the limb with the road nail. However, the small values (<2 mm, Table 3) and non-significant changes ($P \geq 0.093$ for PDmin, PDmax, PDup) indicate that at the level of the midline of the pelvis, the horses' movement remains unaffected by the placement of the road nail.

This movement pattern is different to what is typically measured in lame horses.

Although there is no previous work that directly relates HHD to force asymmetries, it follows logically from Newtonian mechanics that any changes in upward movement amplitudes that are used to calculate HHD must be related to both the peak forces produced (the starting position of the amplitudes during mid stance) and the amount of pushoff. Thus, an increased amplitude of the right tuber coxae relates to decreased force production of the right limb (i.e. the mechanism seen in right hind limb lameness). In contrast, the road nail on the left hindlimb provides the horse with the ability to make more efficient use of the left hindlimb, presumably due to increased grip. Increased grip means the left hindlimb has more time to provide weight bearing and propulsive forces during stance, and it supports farriers' reasoning behind the insertion of road nails.

Future work may seek to use force plate based methods to directly study the amount of force produced during each stance phase. Furthermore, the observed change in HHD (of >3 mm) is in the order of magnitude of pelvic asymmetry changes considered to be significant in the context of equine clinical lameness examinations, and changes of this magnitude can be blocked by diagnostic analgesia. It is hence interesting to see that a small change in shoeing protocol (road nail) is related to consistent but very small changes in the mechanics of movement. Nevertheless, the level of asymmetry measured here is small compared to the amount of asymmetry in most lame horses and also small compared to variability of gait parameters measured [26]. It is hence very important to establish the biological long-term relevance of very small changes in movement asymmetry, such as those reported in the current study.

In this study, tungsten carbide road nails were placed in partly worn horseshoes towards the end of a shoeing cycle; between 5 and 6 weeks after the previous shoeing the nails are considered to be most effective. The function of the tungsten (specifically tungsten carbide) road nail as a provider of grip is related to its greater hardness relative to steel. Tungsten carbide has a hardness value of 9 on the Mohs scale, which is equivalent to 1500 kg mm^{-2}, whereas mild steel has a value of 4–5, equivalent to 150 kg mm^{-2} [27]. Consequently, a steel shoe will wear at a faster rate than the nail over a shoeing cycle, and the road nail will gain increasing prominence towards the end of the cycle, presumably further enhancing its anti-slip characteristics. Investigating this effect, however, was not part of the present study and requires further investigation.

The prominence of the road nail on the underside of the shoe effectively creates a very small lengthening of the limb with the nail compared to the contralateral limb. The effect of artificially lengthening one hindlimb – termed 'orthotic lift' – has been investigated previously using the same approach as used here: upper body movement symmetry based on IMU measurements [28]. Interestingly, midline pelvic (sacrum) movement asymmetry was shown to be affected by lengthening, while tuber coxae movement asymmetry (HHD) was not [28]. This is opposite to the findings of the present study, where HHD was affected by the presence of a road nail but midline pelvic movement asymmetry parameters (PDmin, PDmax, PDup) were not. This may be explained by the fact that the orthotic lift used by Vertz et al. [28] was between 15 mm and 23 mm more exacerbated than the small prominence of the road nail (~2 mm) or it simply means that the effect of the road nail is not due to limb lengthening and that horses are reacting differently to increased grip than to an orthotic lift.

Finally, our study implemented an asymmetrical intervention, i.e. road nails were only used in one limb of a pair of limbs. This contrasts to the normal use of road nails, which are applied to both limbs of a pair. The reason for the asymmetrical intervention was that our assessment with IMUs is based on the principle of assessing upper body movement asymmetry. Hence a symmetrical intervention, i.e. road nails on both limbs of a pair, would not be detectable by this approach. It remains to be investigated whether specific changes in vertical force production can be linked to upper body movement asymmetries in horses without obvious lameness. This would build upon previous work relating lame horses' upper body movement asymmetries to force production [16,17].

5. Conclusion

In this intervention study, it was shown that tungsten carbide road nails placed laterally in one shoe of a hindlimb in horses trotting on tarmac create a small movement asymmetry of the pelvis. This was measured by comparing left and right tuber coxae movement. The data were consistent with a small increase in vertical force production being generated by the limb with the nail compared to the contralateral limb. Road nails are hypothesised to reduce hoof slip, which may allow horses to make more efficient use of their hindlimb when trotting on a tarmac. Further studies should investigate how the number and placement of nails, both on the straight as well as on circles, may affect changes in hoof motion, such as slip time and distance and should also concentrate on establishing the biological long-term relevance of very small changes in movement symmetry such as those reported here.

Author Contributions

PD conceived the study design with assistance from TP and RW. PD and LC collected the data. Data were analysed and interpreted by PD, TP and KH. The manuscript was written by TP, KH and PD with input and approval from all authors.

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Manufacturer's details

Xsens BV, Enschede, The Netherlands

The Mathworks Inc, Natick, MA, USA.

SPSS Inc., Chicago, Illinois, USA.

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Highlights

Pelvic movement symmetry in horses trotting on tarmac can be altered by application of a tungsten road nail to the lateral heel of a hind limb shoe.

Subtle variability in pelvic movement symmetry can be quantified as the difference in displacement amplitude between left and right tuber coxae (hip hike difference).

Changes in pelvic movement symmetry can be explained by increased weight bearing and propulsion in the hindlimb with the road nail.

Ethical Statement

Ethical approval for this intervention study was granted by the Ethics and Welfare committee at the authors' institution (URN: M2017 0120). Informed consent was given by the owners of the horses participating in this study.

Conflict of Interest

We have the following interests: PD is a registered farrier, LC is a registered farrier and TP is owner of EquiGait, a provider of gait analysis products and services. This does not alter our adherence to all policies on sharing data and materials.