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Unilateral-Dominant Lameness Induces Changes in Breakover Duration Symmetry in Equine Walk

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Abstract

Lameness is widely regarded as the most prevalent problem affecting equines globally. Much is understood about the adjustment of upper body posture to reduce loading in an affected limb. However, the relationship between lameness and breakover duration, when the distal limb experiences high tensile stresses, remains an underinvestigated area. Thus, this study aimed to investigate breakover duration at walk in a cohort of horses, quantifying the effect of fore- and hindlimb lameness. It was hypothesized that lameness would induce an asymmetry between breakover durations of affected contralateral limb pairs. Breakover durations of sixteen horses (five sound and eleven lame, as presented by owners) were measured using data collected by hoof-mounted gyroscopes. Breakover durations of the limbs of contralateral pairs were compared, and paired Student's t-tests were used to determine whether differences were significant ($p < 0.01$). A high degree of symmetry was seen in breakover durations of sound horses, with a mean (SD) duration of 168(19)ms and a negligible mean absolute difference (6ms, $p = 0.07$). In lame horses, breakover durations of lame limbs (167(22)ms) were longer than those of contralateral limbs (146(23)ms, $p < 0.001$); and breakover durations of the ipsilateral (160(26)ms) and diagonal (162(24)ms) limbs were equivalent and comparable to those of sound limb pairs. These results indicate that where there is lameness present in a contralateral limb pair, there will be a breakdown in the symmetry of breakover duration, with the most severely affected limb having a significantly longer breakover duration than the contralateral. This pattern should be investigated in the future as a marker to indicate lameness.

Keywords

Breakover; wearable technology; lameness classification; gait analysis; biomechanics; IMU

1. Introduction

In a stride cycle, limb motion consists of swing and stance phases, the latter describing the period from first hoof-ground contact (*hoof-on*) to the instant the toe is lifted (*hoof-off*). The stance phase can further be broken down into instants of primary and secondary impacts [1], during which the hoof is loaded, experiencing ground reaction forces (GRFs) initially applied at a point dorsal to the center of rotation of the distal limb, which creates the extending moment of the digital interphalangeal joint [2]. This is opposed by a flexing moment applied by increasing tension in the deep digital flexor tendon (DDFT) and other soft tissues. When the flexing moment overcomes extending, the heel is lifted from the ground (*onset of breakover*), and the hoof rotates around the toe until it is lifted totally (*hoof-off*) [3]. This terminal part of the stance phase is known as *breakover* [3].

In the literature, there is slight disagreement about the breakover duration at walk as a percentage of stance duration, with one group reporting 10% [4,5] for the forelimbs, in contrast to others who published values of 14.1% [6] and 17(5)% [7]. For the hindlimbs, 15.4% [8] and 13(4)% [7] have been reported.

Most previous studies of breakover duration focused on the effects of different farriery methods **[9–11]** and speed and surface conditions **[12]**. These aimed to assess the effectiveness of farriery techniques to improve musculoskeletal health by influencing breakover mechanics and to evaluate the risk of injury posed by different exercise surfaces and speeds.

In the lame horse, movement adaptations alleviate pain in an affected limb by redistributing loading to other limbs **[13]**, resulting in significantly smaller vertical GRFs in lame limbs compared to compensating limbs **[14–16]**. Clayton *et al.* **[17]** mooted a causal link between breakover duration and the reduction in vertical GRFs observed during lameness. In lame horses trotting over a force plate, they reported that the center of pressure in the lame limb began to move rapidly in the dorsal direction at a relatively early stage of the stance duration resulting in an early onset of breakover and, thus, prolonged breakover duration. They suggested that the lower vertical GRFs experienced by the lame limb were responsible for the prolonged breakover duration as the extending moment they induced would be more easily overcome by the opposing moment created by tension in the soft tissues.

Since this suggestion, only a handful of studies have reported on the relationship between lameness and breakover duration. Small differences have been found at walk between breakover durations of an affected limb at baseline readings and after induction of unilateral forelimb lameness **[18]**. No significant differences were reported between the breakover durations of treated and contralateral forelimbs, suggesting lameness did not affect the left/right symmetry of breakover durations. Studies of trot found the breakover duration of the affected limb was significantly longer than that of the contralateral in cases of severe forelimb lameness caused by a non-articular shoulder fracture **[19]**, chronic sesamoiditis of the fetlock joint **[20]** and fracture of the third carpal bone **[21]**. To the best of the author's knowledge, no previous investigations specifically explored the effect of hindlimb lameness on breakover duration.

The aim of this research was, hence, to investigate breakover duration in a cohort of horses, quantifying the effect of fore and hindlimb lameness. It was hypothesized that lameness would influence breakover duration, inducing a longer breakover in the most severely affected limb compared to the contralateral limb.

2. Materials and Methods

2.1. Horses

Sixteen riding horses (eight geldings; eight mares) of various breeds and uses, including sports and leisure, with a mean (SD) height of 164(9) cm and age of 13(5) years were included **(Table 1)**. Five were presented as sound by the owners (Horses 1-5). These horses had not been referred to a veterinarian with any lameness concerns for at least the past 5 years and had not shown any changes in their performance that might indicate a developing issue.

Eleven horses were also recruited that presented with unilateral or unilateral-dominant lameness (where one limb of the pair was markedly more affected than the other), but no perfectly bilateral lameness at the time of data collection. Among these, three suffered from forelimb lameness (Horses 6-8) and seven from hindlimb lameness (Horses 9-15), while one (Horse 16) had lameness predominating in one forelimb and the diagonal hindlimb. The horses were not assessed by a clinician specifically for the study, but each of them was classified as sound or lame based on the history provided by their owner, provided that they had been assessed by their own veterinarian in the two weeks prior to data collection. The findings of these assessments are recorded in **Supplementary Table 1**. Given that no study-specific veterinary assessment was performed, lameness grades were not obtained

The lack of published data in the literature meant that sample size calculations were not possible during the study design stages, but effect sizes are reported in the results to account for the limited sample size.

2.2. Data Collection and Measuring Protocol

Inertial measurement units (IMUs; Shimmer3 IMU, Shimmer Sensing, Dublin; **Figure 1**) containing tri-axial gyroscopes (range ±2000 deg/s; sampling frequency 200 Hz) were firmly attached to the lateral aspect of the four hooves using sticky-back hook-and-loop fastenings (VELCRO® Brand, Manchester, New Hampshire). Horses were walked in-hand at self-selected speeds along a flat 30m asphalt track, with the central 20m being used for data processing. Three passes were recorded per horse. Trials with significant disturbances (such as the horse trotting or halting) were repeated. The methods were reviewed and approved by The University of Sheffield, Ethics Department (Reference Number 033398), and owners gave informed consent for their animals' involvement.

2.3. Data Analysis

2.3.1. Calculating Temporal Parameters

The hoof-on, -off, and onset of breakover were detected from the angular velocities **(Figure 2)** using previously validated methods **[7,22,23]**. Briefly, the resultant of angular velocity (ω_R) was calculated and filtered using a second-order Butterworth filter with a cutoff frequency of 40Hz. For each stride, the flat portion (stance phase) was identified, and the instant the signal began to rise, at the end of this, was taken to be the onset of breakover (b_{ov}). The highest subsequent peak was taken as hoof-off (h_{off}), and the last peak before the stance phase as hoof-on (h_{on}).

Temporal stride parameters were calculated for each stride cycle of each limb. Stride durations (T_{stride}, ms) were calculated as the time from one hoof-on to the next (Eq. 1).

$$T_{stride} = h_{on_{n+1}} - h_{on_n} \quad (1)$$

Where T_{stride} is the stride duration, h_{on_n} the instant of one hoof-on, and $h_{on_{n+1}}$ that of the next.

Stance durations (T_{stance}, ms) were calculated as the time from hoof-on to the subsequent hoof-off (Eq. 2).

$$T_{stance} = h_{off} - h_{on} \quad (2)$$

Where T_{stance} is the stance duration and h_{off} is the instant of hoof-off.

Breakover durations (T_{BO}, ms) were calculated as the time from the onset of breakover to hoof-off (Eq. 3). Breakover durations were also calculated as a percentage of the stride duration.

$$T_{BO} = h_{off} - b_{ov} \quad (3)$$

Where T_{BO} is the breakover duration, and b_{ov} is the instant of the onset of breakover.

Table 1: Details of the cohort. Horses 1 and 16 were barefoot, while Horse 4 was shod only in front. All other horses were fully shod.

Horse ID	Age (years)	Height (cm)	Lameness state
1-5	13(6)	162(9)	Sound
6-8	16(4)	163(14)	Forelimb lame
9-15	14(5)	164(5)	Hindlimb lame
16	14	168	Left fore & right hindlimb lame
Mean (SD)	13(5)	164(9)	-

Figure 1: Shimmer IMU attached to the lateral aspect of the hoof wall using sticky-back hook-and-loop fastenings.

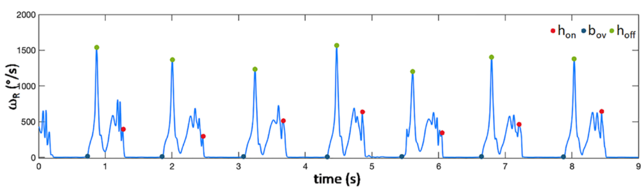

Figure 2: Example of hoof-on (h_{on}, red dots), -off (h_{off}, green dots), and onset of breakover (b_{ov}, indigo dots) detected from resultant of angular velocity (ω_R); seven consecutive stride cycles for one limb are presented.

To investigate stride, stance, and breakover durations, data were split into groups of sound, lame, and opposite limb pairs **(Table 2)**, not including data from Horse 16 (which presented both fore and hindlimb lame). The between-limb differences (those between the sound and contralateral limbs of a sound limb pair, or lame and contralateral limbs of a lame pair) were tested for significance using statistical methods. The breakover durations (ms) of sound limb pairs were found to be not normally distributed by visual inspection of the QQ plots and Shapiro-Wilks test ($p = 0.004$). Therefore, differences between breakover durations of these and the contralateral limbs of sound pairs were tested for significance using a Wilcoxon Signed Rank test. All other datasets proved normal, and significance of between-limb differences was tested using paired Student's t-tests.

2.3.2. Comparing Contralateral Breakover Durations

For each horse, the mean difference ($\overline{\Delta T_{BO}}$, ms, Eq 4) between the breakover durations of the right and left limb of each contralateral limb pair was calculated over the total number of strides.

$$\overline{\Delta T_{BO}} = \frac{1}{n}\sum_{i=1}^{n}\left(T_{BO_R} - T_{BO_L}\right)_i \quad (4)$$

Where $\overline{\Delta T_{BO}}$ is the mean difference between breakover durations of the right (T_{BO_R}) and left (T_{BO_L}) limb of each contralateral limb pair measured over n strides.

The sign of $\overline{\Delta T_{BO}}$ indicated whether the breakover duration of the right (positive) or left (negative) limb of the pair was longer.

Absolute values of $\overline{\Delta T_{BO}}$ for groups of sound, lame, and opposite limb pairs were found to be normally distributed (by visual inspection of QQ plots and Shapiro-Wilks test; $p \geq 0.03$ in all cases). Therefore, absolute values of $\overline{\Delta T_{BO}}$ for the limb pair groups were compared, and differences tested for significance using unpaired Student's t-tests (sound vs. lame, and sound vs. opposite limb pairs) and a paired Student's t-test (lame vs. opposite limb pairs).

Finally, statistical methods were used to test the null hypothesis that, for each individual horse, the mean breakover duration of the left and right limbs of each contralateral limb pair was not significantly different. Shapiro-Wilks test for normality and visual inspection of the QQ plots indicated datasets were normally distributed. Therefore, for each horse, paired Student's t-tests were used to detect statistically significant differences between breakover durations of the left and right limbs of the fore and hindlimb pairs, with $p < 0.01$ indicating significance. The effectiveness of the methods to classify lame horses, detecting lame limb pairs, and identifying the most severely affected limb, were tested on the cohort. All data and statistical analyses were carried out using custom scripts written in Matlab (version 2024Ra).

3. Results and Discussion

A total of 700 walk strides were analyzed, with an average of 41(10) strides per horse.

3.1. Effect of Lameness on Temporal Stride Parameters

There was no difference between mean stride durations of sound and lame horses, and the distributions were similar as both groups consisted of a varied range of horse heights and types **(Figure 3a)**. For sound limb pairs, stance durations were symmetric with no difference between those of the sound and contralateral limbs (**Figure 3b**; $p = 0.4$, effect size = -0.197), in agreement with the literature **[18,24]**. Similarly, no differences were observed between the stance durations of the lame and contralateral limbs of lame limb pairs ($p = 0.96$, effect size = 0.009), indicating that the prevalence of lameness in one limb of the contralateral pair did not affect stance duration symmetry. Moreover, the mean stance durations of the lame group (801(45)ms) were comparable to those of the sound (795(29)ms). Thus, results suggest lameness does not affect the symmetry of the stance durations at walk, in agreement with previous literature **[24]**.

For sound limb pairs, recorded breakover durations were slightly longer (21(2)% of stance duration) than previously reported **[4–6,8]**, which may be due to cohort morphology. In literature, four French Trotters of height 158(4)cm recorded a mean breakover duration of 10% **[4,5]** of the stance duration, while five horses of various breeds and heights 143-156 cm recorded breakover duration of 15% [6]. In the present study, horses were also of various breeds, with a larger range of heights (147-178 cm) and taller mean height (164 (9)cm) than in previous reports which may explain why the average breakover durations recorded here were longer. The disagreements in breakover duration, here and in the literature, warrant further investigation.

Breakover durations of the two limbs of sound limb pairs showed negligible differences (**Figure 3c** and **3d**; $p = 0.07$, effect size = -0.3), reflecting the symmetrical nature of healthy walk. One publication [18] reported a significant difference between the breakover durations of sound and contralateral limbs of sound forelimb pairs. However, the magnitude of that difference (4ms) was negligible. Thus, it can be concluded that there should be left/right symmetry of breakover durations in fore and hind contralateral limb pairs at walk, in a sound horse.

A breakdown in the symmetry of breakover durations emerged for lame limb pairs. The mean breakover duration of the lame limb (**Figure 3c**, solid red box; 167(22)ms) was comparable to that of sound limb pairs (168(19)ms), with a 2ms difference. In contrast, the breakover duration of limbs contralateral to lame limbs (**Figure 3c**, empty red box) was 14% shorter (146(23) ms, $p < 0.0001$, effect size = 0.9). These results also hold when breakover is considered normalized to the percentage of stride duration **(Figure 3d)**, with a mean of 13 (2)% for lame limbs and significantly ($p < 0.0001$) lower mean of 11 (2)% for those contralateral to them. The results support the hypothesis that lameness induces a longer breakover duration in the lame limb compared to the contralateral limb.

Previously, breakover duration was reported to increase with the induction of Grades 1 (+2ms), 2 (+3ms), and 3 (+1ms) lameness, compared to baseline values [18], at walk. These values are significantly smaller than the differences found in the current study, and no differences were reported between breakover durations of the lame limb and that contralateral to it. There are several reasons why our results may differ. Firstly, the earlier study recorded data over a surface covered by a 9.3mm thick, rubberized mat. This may have acted as a cushion, attenuating some of the impact of the hoof-surface collision, and thus relieving discomfort due to shockwaves [25] traveling up the painful limb and reducing the need for the horse to adopt such a pronounced compensatory movement as those horses in the current study, where data was collected on a hard surface. The lameness models used may have also had an effect. Moorman *et al.* [18] used a method of sole pressure to induce unilateral lameness in six sound horses. While this method has been widely used to stimulate a reversible and controllable lameness [14,24,26], we suggest that the compensatory mechanisms it induces may not comprehensively represent those adopted by horses suffering spontaneous lameness (as in the current study; **Supplementary Table 1**) the causes of which can be many varied and complex.

A prolonged breakover has been associated with a longer toe length and thus an increase in the risk of developing specific pathologies (such as navicular disease [27] or tendon injury [3,7,9]) as a result of increased tensile stresses in the DDFT and impar ligament, and related increased compression of the navicular bursa and navicular bone [3]. However, the diverse range of lameness causes represented in this cohort **(Supplementary Table 1)** suggests that not only can prolonged breakover predispose an animal to injury or disease, but it may also develop as a result of underlying pathologies. These results support the proposal of Clayton *et al.* [28] that the lower GRFs seen in lame limbs might allow the earlier onset of breakover in the affected limb and, hence, a longer breakover duration. Thus, we suggest breakdowns in the left/right symmetry of breakover duration may develop as a coping strategy for accommodating lameness.

The result is perhaps surprising as persistent lameness is often believed to lead to increased hoof angles and a more upright dorsal hoof wall [29] which would tend to shorten breakover duration. However, in literature, only a small and statistically insignificant difference in hoof angle has been reported to support this claim (53 (3)° for lame limb compared to 52 (4)° for non-lame, $p = 0.4$ [30]). Furthermore, other studies have found decreased hoof angles (characterized by long toes and low heels) to correlate with both fore [31] and hindlimb [32,33] lameness, and poor performance [34]. In these studies, breakover durations were not reported but, had they been, they may have been found to be prolonged as a result of the long toe. The findings of these and other publications, along with the results of the current study indicate that further kinematic studies are needed to understand whether the relationship between hoof angle and lameness is a *cause* or *effect* relationship [33], with it being unknown whether low hoof angles precede the onset of lameness or vice versa [32].

Hoof imbalance, particularly of the hindlimbs, has been a consistent clinical finding in horses with back soreness [35,36]. While hoof balance was not assessed in the present study, this previous finding could support a hypothesis that the effect of axial-related lameness (Horses 11-13) on breakover duration might be connected to hoof imbalance. Again, this raises the question of whether the association between hoof morphology and lameness is cause or effect, with Melo *et al.* suggesting that hoof imbalance predisposes horses to musculoskeletal pathologies [36]. Further studies would be needed to answer these questions.

Table 2: Definition of groups into which limb pairs were sorted for analysis. The name of the group, definition, and examples of which limbs would be assigned to each are provided. LF = left forelimb; RF = right forelimb; LH = left hindlimb; RH = right hindlimb.

Group	Description	Example
Sound	Both contralateral limb pairs (fore and hind) of each sound horse, with limbs dubbed *sound* and *contralateral*.	The forelimb- LF (sound) and RF (contralateral)- and hindlimb pair- LH (sound) and RH (contralateral)- of a sound horse.
Lame	The *lame* and *contralateral* (with respect to lame limb) limbs of lame horses.	LF lame horse: LF (lame) and RF (contralateral). RH lame horse: RH (lame) and LH (contralateral).
Opposite	The *ipsilateral* and *diagonal* (with respect to lame limb) limbs of lame horses.	LF lame horse: LH (ipsilateral) and RH (diagonal). RH lame horse: RF (ipsilateral) and LF (diagonal).

Standard deviations of breakover duration were large for all groups, ranging from 17ms to 22ms, reflecting the highly varied nature of both sound and lame cohorts. As the phenomenon is dependent on individual hoof shape [3] as well as overall stride duration and, thus, morphology of the horse, breakover duration could vary substantially between subjects. Hence, actual mean values of breakover duration might prove to be horse-specific. Nonetheless, the pattern of symmetry in breakover duration of sound limb pairs and asymmetry in lame limb pairs is expected to be maintained. Further studies using varied cohorts are needed to verify this.

The pairs of outliers identified in **Figure 3c** were attributable to the forelimbs of sound Horse 4 and lame Horse 8, which were also the tallest horses studied (178cm and 174cm, respectively). These horses also recorded the longest breakover when normalized to total stride duration **(Figure 3d)**. The results could be due to the horses' heights. Despite appearing as outliers, both horses follow the pattern of their respective groups—Horse 4's forelimbs have similar breakover durations, and Horse 8's lame forelimb demonstrates a longer breakover duration compared to the contralateral limb.

The small absolute mean difference between the breakover duration of the two limbs of sound limb pairs (**Figure 4**, $|\overline{\Delta T_{BO}}|$=6(5)ms, n = 10), seems to confirm the well-reported fact that horses demonstrate some natural asymmetry due to sidedness [37–39]. As a direct practical application of these results, $|\overline{\Delta T_{BO}}|$ of sound limb pairs could be used to establish a threshold of allowable difference to distinguish between natural sidedness and lameness. However, a larger cohort of sound horses would be needed to ensure the robustness and generalizability of these results.

Compared to the sound group, $|\overline{\Delta T_{BO}}|$ obtained for the lame limb pairs (**Figure 4**, 21(5)ms, n = 10) was more than three times greater ($p < 0.001$), indicating a much higher degree of asymmetry, with power calculations revealing an observed power of over 99% ($\alpha = 0.01$). Thus, results suggest there exists a real significant difference between $|\overline{\Delta T_{BO}}|$ values recorded from sound limb pairs compared to lame. $|\overline{\Delta T_{BO}}|$ for opposite limb pairs (7(5)ms) was equivalent to the value obtained for sound pairs ($p = 0.7$) and 67% smaller ($p < 0.001$) than that obtained for lame pairs. The degree of symmetry of opposite limb pairs being comparable to that of sound indicates they did not demonstrate a compensatory effect due to lameness. In studies of upper body movement symmetry, compensatory lameness mechanisms are widely reported, and methods of lameness quantification which use upper body parameters can be complicated [40]. If they continue to prove robust to the effects of compensatory lameness, methods of breakover analysis will surely be a useful addition to the currently used upper body symmetry analyses as a means of distinguishing true lameness from compensatory.

The outliers identified in lame and opposite limb pair groups **(Figure 4)** were the results of Horse 9. Although the magnitude of $|\overline{\Delta T_{BO}}|$ of the opposite limb pair (20ms, Horse 9_F) was higher than those recorded for other horses in the group, it was still substantially (39%) smaller than that recorded for the corresponding lame limb pair (33ms, Horse 9_H). Hence, despite appearing as an outlier, the behavior of Horse 9 fitted the cohort pattern. These results indicate that a pattern in breakover duration was observable for the sound and lame cohorts, with sound limb pairs and those opposite to a lame pair displaying a high degree of symmetry but a breakdown of this symmetry being seen in lame limb pairs. The results confirm the study hypothesis that longer breakover durations, compared to the contralateral, are a feature characteristic of lame limbs. Furthermore, **Figure 4** indicates that the result is the same and holds for both horses suffering axial- and appendicular-related lameness, as there is no distinction between the behavior of each group. Therefore, comparing concurrently recorded breakover durations of the left and right limbs of contralateral pairs may prove a valuable addition to methods to detect and monitor unilateral-dominant lameness attributable to both axial- and appendicular-pathologies.

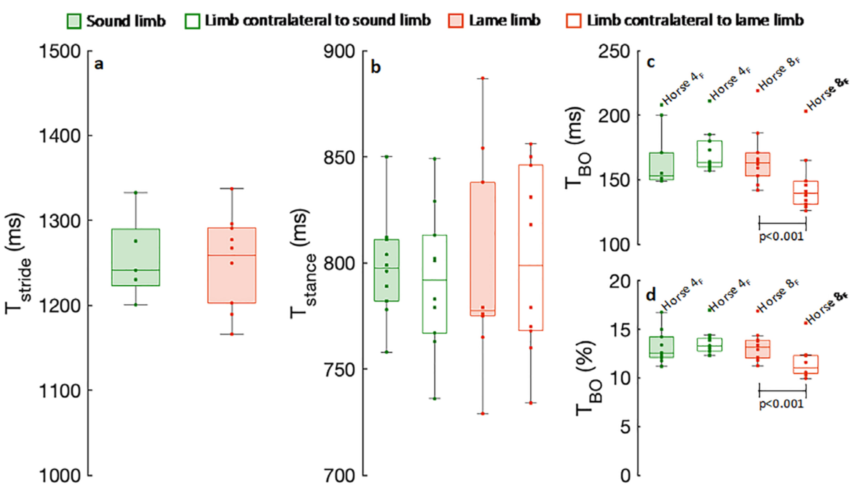

Figure 3: Stride (T_{stride}, a) and stance durations (T_{stance}, b) in ms, and breakover durations in ms (T_{BO}, c) and as percentage of stride duration (T_{BO}, d). Temporal parameters are shown for limb pairs of sound horses (sound and corresponding contralateral limbs) and lame limb pairs of fore and hindlimb lame horses (lame and corresponding contralateral limbs). Solid green boxes represent the sound limbs and empty green boxes represent those contralateral to them; solid red boxes represent lame limbs and empty red boxes represent those contralateral to them. Individual points are shown as dots, and outliers are labeled. Significant differences are indicated with *p*-value. These results do not include Horse 16.

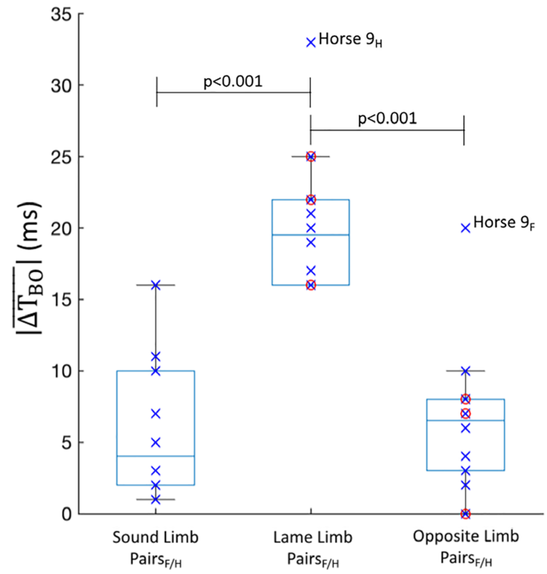

Figure 4: Absolute mean values of the difference in breakover durations of the limbs of fore (F) and hind (H) contralateral limb pairs ($|\overline{\Delta T_{BO}}|$, ms) for sound, lame, and opposite limb pairs. Significant differences are indicated with *p*-values, and outliers are labeled. For lame and opposite limb pairs, results of horses with axial-related lameness causes (Horses 11-13) are highlighted with red circles, compared to those with appendicular-related causes. These results do not include Horse 16.

3.2. Breakover Duration as a Tool for Lameness Detection

An example of how, with further validation studies, breakover data could be used to classify lameness in individual horses is presented in **Table 3**. The presence of a statistically significant difference ($p < 0.01$) between breakover durations of a contralateral limb pair, recorded over a given number of strides, would indicate lameness (bold values). Sensitivity analyses revealed that ten strides were sufficient to establish steady values of $\overline{\Delta T_{BO}}$, while thirty were required to obtain steady *p*-values from the paired Student's t-tests of lame limb pairs. The *p*-values for sound limb pairs did not converge to a steady value, regardless of the number of strides analyzed, as expected. Thus, it is advised that a minimum of thirty strides be recorded for the application of these methods.

No lameness was detected for the fore or hindlimbs of the five sound horses ($p \geq 0.03$). The method correctly classified all lame horses, with limb pairs where lameness was prevalent displaying statistically significant differences in breakover duration. Furthermore, the sign of $\overline{\Delta T_{BO}}$ correctly identified whether lameness predominated in the left (negative) or right (positive) limb in every case. For both fore and hindlimb lame horses, $\overline{\Delta T_{BO}}$ of the lame limb pair was substantially larger in magnitude than that of the opposite limb pair. Indeed, in all cases but one (Horse 9), absolute $\overline{\Delta T_{BO}}$ of the lame limb pair was at least 90% longer (range 16 to 33ms) than that of the opposite limb pair (range 0 to 10ms). This supports the suggestion that, with a larger cohort, threshold values of $\overline{\Delta T_{BO}}$ might be used in the future to classify lame and sound limb pairs.

Horse 16 was presented with severe lameness of the left fore and lameness of the right hindlimb. This was one of only three horses currently out of work due to lameness **(Supplementary Table 1)**. The severity of Horse 16's forelimb lameness appears to be reflected in the magnitude of $\overline{\Delta T_{BO}}$ (51ms), the highest recorded. Future studies could determine whether the magnitude of $\overline{\Delta T_{BO}}$ correlates with the severity of lameness. Horse 16's results also indicate that the methods might be used to assess horses with concurrent fore and hindlimb lameness, provided one limb of each contralateral pair is sufficiently more affected than the other to allow the detection of breakover asymmetry. Further studies on larger populations of horses, with complex multi-limb lameness, are of course needed to explore this hypothesis.

3.3. Limitations and Future Work

The most significant limitation of the work was that lameness states were not classified and graded by the same veterinarian at the time of data collection. While all lame horses had been assessed by a vet during the two weeks prior to data collection, initial classification depended on the history provided by the owner. Future studies should prioritize having a clinician involved for subjective lameness assessment using, for example, the AAEP scale. It may also be highly beneficial to use another system for lameness detection concurrently (for example one which analyses upper body movement) to compare results obtained by both systems.

Table 3: Mean (SD) values of the difference in breakover duration of right and left limbs ($\overline{\Delta T_{BO}}$, ms) for the fore and hindlimb pairs of all horses and p-value result of the paired Student's t-tests. Clinical observations indicate whether the horse was presented as sound (S) or having lameness predominating in the left (L) or right (R) fore (F) and/or hindlimb (H). Values in bold indicate where the difference was significant ($p < 0.01$). Horse 16, with lameness of both left fore (LF) and right hindlimb (RH), is presented in the bottom row.

Horse ID	Forelimbs (ms)		Hindlimbs (ms)		Clinical observations
	Mean(SD)	*p*-value	Mean(SD)	*p*-value	
1	7(18)	0.08	-3(22)	0.5	S
2	10(33)	0.1	-11(30)	0.03	S
3	1(27)	0.7	5(34)	0.4	S
4	2(30)	0.6	1(19)	0.8	S
5	-16(40)	0.03	3(29)	0.6	S
6	**21(34)**	**<0.001**	3(34)	0.4	RF
7	**20(18)**	**<0.001**	2(17)	0.3	RF
8	**16(33)**	**0.006**	-4(36)	0.5	RF
9	-20(38)	0.01	**-33(32)**	**<0.001**	LH
10	-7(22)	0.03	**16(14)**	**<0.001**	RH
11	-8(16)	0.02	**22(21)**	**<0.001**	RH
12	0(17)	0.8	**25(18)**	**<0.001**	RH
13	-7(15)	0.02	**16(26)**	**<0.001**	RH
14	-10(40)	0.3	**19(16)**	**<0.001**	RH
15	6(36)	0.3	**-17(24)**	**<0.001**	LH
16	**-51(23)**	**<0.001**	**13(12)**	**<0.001**	LF, RH

In a future study, hoof morphology ought to be recorded as trimming **[41]** and shoeing **[10]** are known to have a significant effect on the shape of the hooves, although the latter has been found to affect breakover duration only insignificantly. As the left and right hooves of contralateral pairs tend to be trimmed at the same time and undergo the same shoeing treatment, it is anticipated that the methods of breakover duration symmetry analysis will hold, regardless. Similarly, future studies might also include an assessment of hoof balance, given that hindlimb hoof imbalance appears as a consistent clinical finding in the presence of back soreness **[35,36]**.

This cohort, although larger than many similar studies **[18,42]**, was small. However, the results are extremely useful as they allowed sample size calculations to be conducted to inform future study design. Using $|\overline{\Delta T_{BO}}|$ values for sound (n = 5) and lame (n = 4) forelimb pairs revealed a cohort of twenty-one sound and seventeen forelimb lame horses would be needed to establish that there exists a real significant difference between the $|\overline{\Delta T_{BO}}|$ values of sound and lame forelimb pairs (power 90%, α = 0.01). The results of sound (n = 5) and lame (n = 8) hindlimb pairs indicated that eight sound and five hindlimb lame horses would be needed to prove a real difference between $|\overline{\Delta T_{BO}}|$ of sound and lame hindlimbs (power 90%, α = 0.01).

4. Conclusion

In cases of lameness, lame limbs were found to have a significantly longer breakover duration at walk than the contralateral limb of the pair. With further validation, this finding could form the basis of a valuable tool for the detection and assessment of lameness, requiring the horse to be assessed only at walk. The tool will be a beneficial addition to the current state-of-the-art methods based on upper body motion symmetry, particularly if the finding continues to prove robust to the effects of compensatory lameness.

Supplementary Materials

Morphological details of the cohort of sound and lame horses. The lameness histories of lame horses are given. Horses are organized into sound, forelimb lame, hindlimb lame, and the one horse (Horse 16) which had severe lameness in the left fore (LF) and right hind (RH).

Authors' Contribution

E.V.B: Conceptualization, formal analysis, investigation, writing, reviewing, and editing; C.M.: Conceptualization, reviewing, and editing.

Data Availability

The data underpinning this research is available at: https://figshare.com/s/dfec5cdac816ff46cfcd.

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Conflicts of Interest

The commercial funder Worldbase Ltd. is a manufacturing company, specializing in agricultural machinery, and currently has no products or services, existing or in design, related to the content of this research. Funders had no role in study design, data collection and analysis, decision to publish, or manuscript preparation.

Ethical Approval

The study was reviewed and approved by The University of Sheffield, Ethics Department (Reference Number 033398), and owners gave informed consent for their animal's involvement.

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