Wearable Sensors for

Equine Lameness Quantification

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Despite the short list of authors on the associated publications, this research has been realised only through the contributions of many. I have been humbled by the generosity of participants (and their owners!) and wish to acknowledge every person who selflessly lent horses, donned running shoes or supplied cups of tea. Also, to thank my ever-tolerant friends, who still ring, despite the fact I have been mostly AWOL for years.

Finally, my gratitude always for two other mentors- my wonderful sister, Holly and my muse, Flick

-the pony who started it all.

"If you want that PhD, it's yours!"

Jason Peter Dickinson,
My Uncle and friend,
1st August 1971-
15th December 2018

Abstract

Lameness remains the most common and significant problem affecting equines, globally. Current methods of lameness assessment, however, are still predominantly subjective and have repeatedly been proven unreliable, particularly for mild cases. Hence, there is demand for a comprehensive quantitative system to detect and assess early-stage lameness, facilitating timely intervention, optimising clinical outcomes and improving welfare. Thus, the overall aim of this thesis was to develop methods to quantify equine gait suitable for lameness detection and assessment under field conditions, with specific focuses on usability in diverse cohorts of horses and suitability for easy integration into training or clinical settings.

First, methods to detect gait events (hoof-on and -off) using distal limb mounted IMUs have been explored. Newly developed pastern-based methods proved more accurate and precise than the current state-of-the-art when tested on a hard control surface and maintained high accuracy on grass and sand. Explored methods were then used to investigate the hypothesis that breakover duration would be impaired in lame horses. Results highlighted a loss of symmetry in the left/right breakover durations of lame fore and hindlimb pairs at walk, with lame limbs having significantly longer breakover durations than contralateral. A proposal was hence made as to how this pattern might be used as a robust quantitative tool for lameness assessment. Finally, the effects that this asymmetry would have on the upper body motion symmetry were investigated. It was verified that trot was more informative than walk, when using methods from literature to quantify upper body movement symmetry. While no strong correlations were found between breakover duration symmetry and upper body motion symmetry in this preliminary study, the results highlighted some trends and enabled formulation of new hypotheses for future investigations on the subject. In conclusion, this thesis presents two valuable tools for gait quantification - one for gait event detection the other for lameness assessment - which can easily be implemented under field conditions in a variety of horse types.

Publications and Presentations

In Print:

1. **Briggs EV**, Mazzà C (2021) "Automatic methods of hoof-on and -off detection in horses using wearable inertial sensors during walk and trot on asphalt, sand and grass". PLoS ONE 16(7):e0254813. https://doi.org/10.1371/journal.pone.0254813

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2. **Briggs EV**, Mazzà C. "A Novel Method for Equine Gait Event Detection". ISB 2021, Stockholm, Sweden [online].
3. **Briggs EV**, Mazzà C. "Effect of unilateral-dominant lameness on breakover duration during equine walk". Insigneo Showcase 2022, Sheffield, UK.

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2. **Briggs EV**, Mazzà C. "Detecting equine gait events in field conditions". ESS 2021, Texas, USA [online]. Exercise Science Graduate Student Competition: 2nd Place
3. **Briggs EV**, Mazzà C. "Lameness Influences Breakover Duration in Horses". ESB 2022, Porto, Portugal.
4. **Briggs EV**, Mazzà C. "A novel tool to detect equine lameness using breakover at walk". BioMedEng22, London, UK.

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Declaration

I, the author, confirm that the Thesis is my own work. I am aware of the University's Guidance on the Use of Unfair Means (*www.sheffield.ac.uk/ssid/unfair-means*). This work has not previously been presented for an award at this, or any other, university.

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Chapter 3 of this thesis is based on the content of a published paper titled "Automatic methods of hoof-on and -off detection in horses using wearable inertial sensors during walk and trot on asphalt, sand and grass" and Chapter 4 on a manuscript which is currently in preparation titled "Unilateral-dominant lameness induces changes in contralateral limb breakover duration at walk". This work was carried out in collaboration with the named co-author. In these studies, I developed the protocols and collected data from subjects. I also contributed to the conceptualisation, design and implementation of the data processing methods as well as analysis and interpretation of the results. I led in the manuscript drafting, figure and table preparation, and was responsible for the submission and peer review processes.

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Claudia Mazzà — Date: 12th April 2022

Chapter 1 Definition of Equine Gait

1.1 Introduction

The Collins English dictionary defines gait as a "manner of walking or running" and, especially for horses and dogs, "the pattern of footsteps at various speeds… each pattern being distinguished by a particular rhythm and footfall"[1]. Similarly, Hildebrand, who contributed pivotal early works on the definition of quadrupedal gait, described gait as "a manner of moving the legs in walking or running"[2]. In this research, the focus will be on the two symmetric gaits of equine walk and trot and how they can be measured for the detection and quantification of lameness. Lameness is not only a significant welfare concern but also the cause of substantial performance losses in horses. Being the heaviest economic burden[3–5] and prevalent the world over[6–10], the early detection and treatment of lameness is of the utmost importance to equestrian professionals and hobbyists.

The adoption of standardised terminology in equine gait analysis research is integral to facilitate easy dissemination of information[11]; hence, in this chapter, naming conventions which are used throughout the thesis, many extracted from previous advisories[12], and the temporal parameters which will be investigated are defined.

1.2 General Terminology

Conformation refers to the horse's shape and structure, primarily dictated by the geometries of the bones and musculature, which can influence locomotion[13]. Conformation is intrinsically related to the breed and use of the horse, with many having been selectively bred to optimise their shape for specific applications[14,15]. For example, the Tennessee Walking Horse has been bred over many generations to have long sloping shoulders and hips and a short back to maximise their range of motion to achieve the breed-specific running walk. In nature, natural selection has also had an impact on equine conformation with Shetlands having bred naturally in the wild to produce a breed whose legs are short and thick, making them sure-footed and well adapted to navigating the rough terrain of their native habitat on the moors of the Shetland Islands.

1.2.1 Directional terms

Standard terms will be used to describe directions and locations of body parts relative to each other (Fig 1.1). The terms **fore** and **hind** will be used to refer to the cranial and caudal ends of the horse, respectively. Locations lying on the dorsal aspect of the craniocaudal axis of the horse will be referred to as **midline** locations.

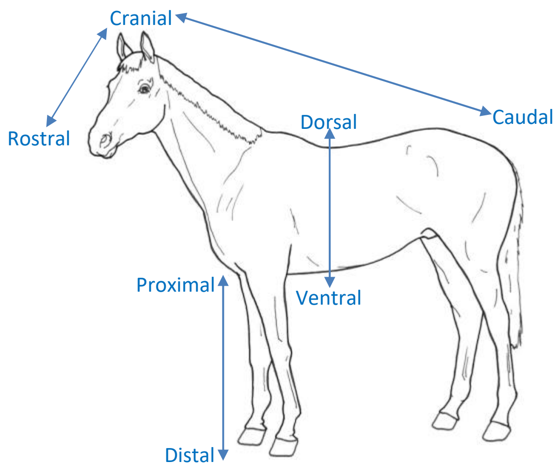


Figure 1.1 schematic of directional anatomical term.

1.2.2 Anatomical terms

The terms which will be used to name features of the body in this research are given (Fig 1.2). The **limbs** are the left fore (LF), right fore (RF), left hind (LH) and right hindlimb (RH). The **poll** refers to the highest point on the head, between the ears; the **withers** to the bony ridge at the base of the neck above the region of the cranial thoracic vertebrae; and **croup** is the term given to the highest bony protuberance, above the tuber sacrale. The **girth** is on the ventral side of the trunk, central and behind the shoulders; beneath the girth is the ascending pectoral muscle. The **sternum** is the breastbone, which can be palpated as a bony protuberance between the descending pectoral muscles.

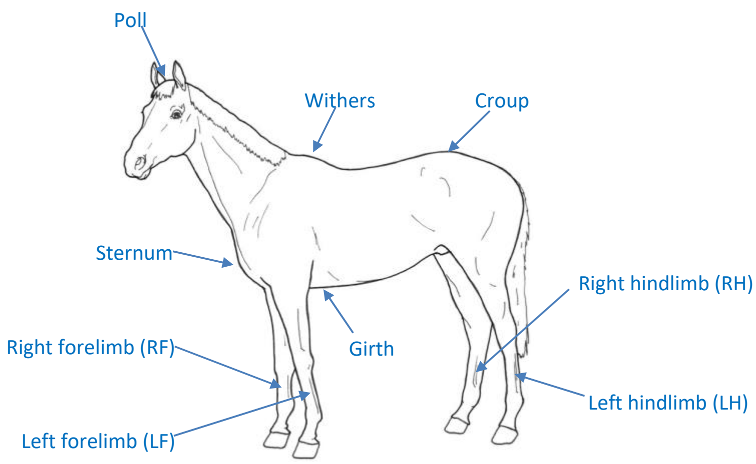


Figure 1.2 schematic of anatomical terminology.

For the determination of footfalls, the spatiotemporal parameters of the distal limbs must be investigated. In the following chapters, gait analysis equipment is mounted at different locations on the limbs. A diagram of the fore and hindlimb is presented (Fig 1.3), annotated with the terms which will be used to refer to the different parts of the limbs.

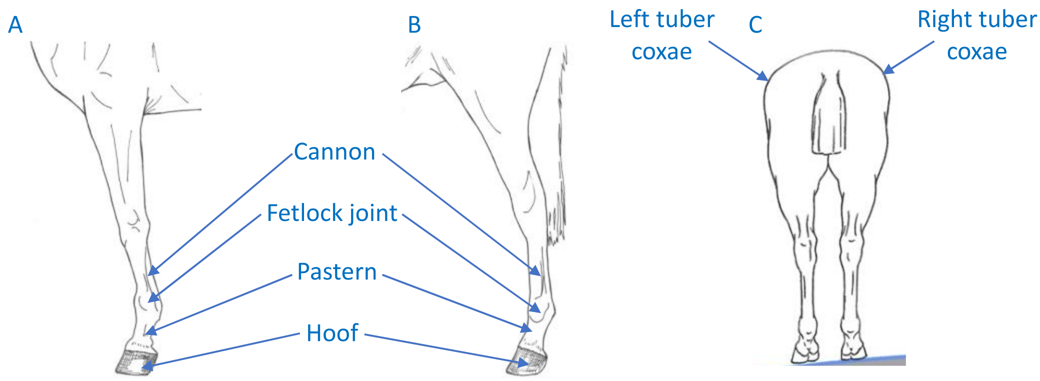


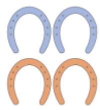
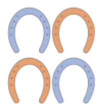
Figure 1.3 schematic of limbs and pelvis. Diagrams are of horse's fore (A) and hindlimb (B), and the relevant parts of the pelvis (C).

Cannon is used to refer to the area at the level of the third metacarpals (forelimbs) and metatarsals (hindlimbs), commonly called the cannon bones. The area between the fetlock joint and the hoof will be referred to as the **pastern**, being at the level of the proximal phalanx, commonly called the long pastern bone. The left and right **tuber coxae** (plural **tubera coxae**) are the points of the pelvis and can be identified by palpation as bony protuberances.

1.2.3 Limb pairs

Descriptions in terms of **limb pairs** are often convenient for describing quadrupedal gait. In this thesis, the terms **ipsilateral**, **contralateral** and **diagonal** are used to describe limb pairs (Table 1.1).

Table 1.1 definition and illustration of limb pairs.

Pair	Definition	Schematic
Ipsilateral	Fore and hindlimb of the same side. Left (blue) and right (orange) ipsilateral limb pairs	
Contralateral	Left and right fore or hindlimbs. Front (blue) and back (orange) contralateral limb pairs	
Diagonal	Hindlimb of one side and forelimb of opposite. Right (blue) and left (orange) diagonal limb pairs	

1.3 Temporal Stride Parameters

1.3.1 The stride cycle

The stride cycle is characterised by the gait events **hoof-on**, at the first contact between hoof and ground, and **hoof-off**, at the final contact as the hoof is lifted. These gait events delimit the **swing** and **stance** phases of the stride cycle, when the hoof is in contact with the ground and swinging through the air, respectively.

The timing of consecutive gait events of the same type can be used to segment gait into periods of **stride** cycle. In this thesis, instances of consecutive hoof-on events ($\mathrm{h}_{\mathrm{on}_\mathrm{n}}$ and $\mathrm{h}_{\mathrm{on}_{\mathrm{n}+1}}$) are used to calculate the stride duration (T) according to Eq 1.1.

$$\mathrm{T} = \mathrm{h}_{\mathrm{on}_{\mathrm{n}+1}} - \mathrm{h}_{\mathrm{on}_\mathrm{n}} \quad (1.1)$$

The stance duration (t) is calculated as the time between the hoof-on (h_{on}) and subsequent hoof-off (h_{off}) event of the same limb (Eq 1.2) and can be considered in units of time or as a percentage of total stride duration.

$$t = h_{off} - h_{on} \qquad (1.2)$$

The time from hoof-on to the middle of the stance phase- **midstance**- is a decelerative phase in which the hoof is slowed to stationary, while the midstance to hoof-off is a propulsive phase in which potential energy is converted to kinetic and the limb accelerates forwards into the swing phase[16]. The point at which the heel begins to lift from the ground is called the onset of **breakover** (b_{ov}) and the time between this and hoof-off forms the breakover duration (T_{bo}), calculated by Eq 1.3. An illustration of the stance phase and breakover, which is estimated to last around 20% of the duration of stance phase in sound horses walking[17] is given (Fig 1.4).

$$T_{bo} = h_{off} - b_{ov} \qquad (1.3)$$

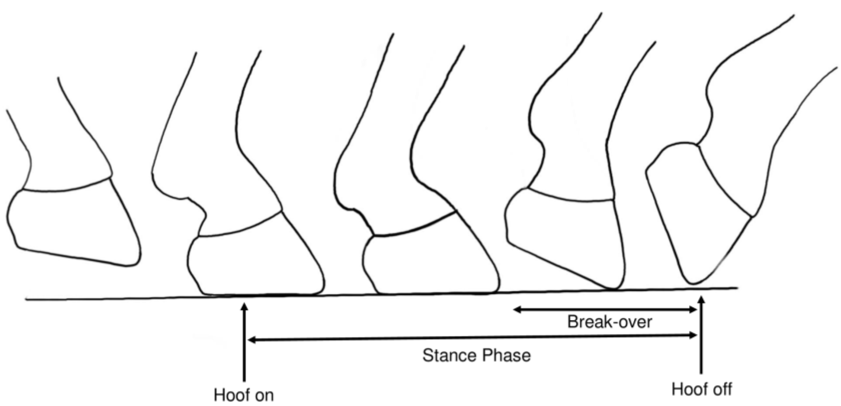


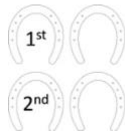
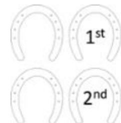
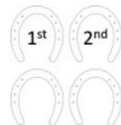
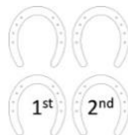
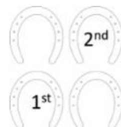
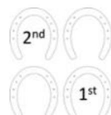
Figure 1.4 diagram of the events which characterise the stride cycle.

In human gait analysis, the number of strides completed per unit time is referred to as the cadence. However, in equine sports, particularly dressage, cadence is a subjective term used to describe the combination of rhythm and impulsion demonstrated in a gait. For this reason, it is suggested that **stride frequency** be used instead [12].

1.3.2 Step Variables

The interlimb timing of gait events can be useful in describing the coordination between limbs and, for the purpose of this research, a number of **steps** are defined which describe the timing between hoof-on events of different limbs (Table 1.2). The schematic illustrations describe the order of footfalls in the step. The left and right describe the ipsilateral steps; front and back the contralateral steps; and left and right diagonals the diagonal steps.

Table 1.2 definition of the steps, including equations to calculate them and schematic illiustrations which indicate the order in which the relevant hoof-on events occur.

Step	Definition	Calculation	Schematic
Left	From LF hoof-on to LH hoof-on	$\mathrm{LH_{on}} - \mathrm{LF_{on}}$ (1.4)	
Right	From RF hoof-on to RH hoof-on	$\mathrm{RH_{on}} - \mathrm{RF_{on}}$ (1.5)	
Front	From LF hoof-on to RF hoof-on	$\mathrm{RF_{on}} - \mathrm{LF_{on}}$ (1.6)	
Back	From LH hoof-on to RH hoof-on	$\mathrm{RH_{on}} - \mathrm{LH_{on}}$ (1.7)	
Left Diagonal	From LH hoof-on to RF hoof-on	$\mathrm{RF_{on}} - \mathrm{LH_{on}}$ (1.8)	
Right Diagonal	From RH hoof-on to LF hoof-on	$\mathrm{LF_{on}} - \mathrm{RH_{on}}$ (1.9)	

1.4 Healthy Gait Patterns

As mentioned previously, the movement strategies, or paces, of horses can be subdivided into distinct **gaits** which are classified based not only on the speeds they reach but also the sequence of footfalls. Much of the seminal research into quadrupedal gait was conducted by Hildebrand who sought to develop methods of gait description, looking at species-specific gait patterns with relation to speed, body conformation and size, manoeuvrability and ancestry[2,18]. These early publications, and those which ensued have been used to construct the following sections.

The four basic gaits common to all horses are walk, trot, canter and gallop. Some, so-called gaited breeds, have been selectively bred to have additional gaits[14,15], these include the Icelandic horse, with the additional gaits of tölt and flying pace.

Discrimination between **sound** and **lame** gait is a significant issue for all in the equestrian community as underlying issues which manifest as lameness, remain the most common cause of performance impairment and reason for veterinary intervention across all equestrian disciplines worldwide[6–10,19]. A sound horse is one which demonstrates no detectable pathological deviation of gait from that which is considered ideal; conversely, lameness is the term used to describe an abnormal stance or gait which can be caused by a functional or structural disorder of the locomotor system, or neurological issue[20–22]. Lameness is not, in itself, a pathology rather it is a clinical sign of an underlying issue[23,24].

During subjective clinical workups, the experienced clinician will visually assess a range of local, regional and whole-body motion, including upper body and limb movement, to identify lameness[25–28]. Amongst the parameters scrutinised, the degree of symmetry in the horse’s movement is commonly used to determine whether the horse is lame[29]. Hence, the inherently symmetrical gaits of walk and trot[2,30] are most commonly used to assess the state of lameness and these are the gaits focussed on in this research. A detailed description of the effect of lameness on equine gait is given later in this chapter (section 1.5). To recognise lameness and understand its mechanics, it is first imperative to appreciate the characteristics of a healthy walk and trot.

1.4.1 Healthy walk stride pattern

Healthy equine walk is a four-beat gait with equal timings between footfalls, the sequence of which is illustrated in Fig 1.5. It exhibits right-left bipedal symmetry[31] and consists of periods of alternating bi- and tripedal limb support. There is no suspension phase, with large overlaps existing between stance durations of different limbs, each stance duration lasting 65-75% of a total stride duration[31].

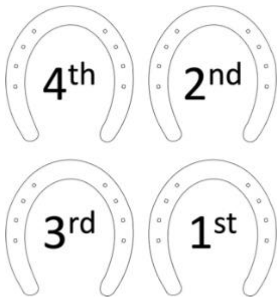


Figure 1.5 illustration of the sequence of hoof-on events for walk.

At walk, the vertical motion of the trunk and head are biphasic[32] and, in the sound horse, the two oscillations are expected to be approximately identical. Fig 1.6 has been created, after scrutiny of the literature[33,34], to illustrate the relationship between gait events and body motion. Timing of stance and swing phases of the four limbs appear as a Hildebrand-style gait diagram[18] at the bottom of the figure, and the synchronous vertical movements of the midline are illustrated above. The croup oscillates with its highest positions coinciding with the midstance of the left and right hind limbs, consecutively[25]; the hindlimb hoof-on occurs as the croup is moving downwards and hoof-off as it moves upwards. The poll behaviour in the vertical direction is in phase with that of the croup and is expected to be 9.1(3.4)cm in total for a sound walk[32]. The timing of vertical poll displacements, relative to the temporal stride parameters, has been found to be a mechanism of energy expenditure minimisation[32], when the head and neck are modelled as an inverted pendulum[35], which explains why the poll moves in phase with the croup. Forelimb hoof-on events occur as the poll is moving upwards and hoof-off events as it is moving downwards; the lowest positions of the poll coincide with the midstance of the forelimbs, consecutively. The withers move out of phase with the croup and poll, with the highest wither positions coinciding with the midstance of each forelimb, sequentially[32] and the lowest position with the midstance of the hindlimbs.

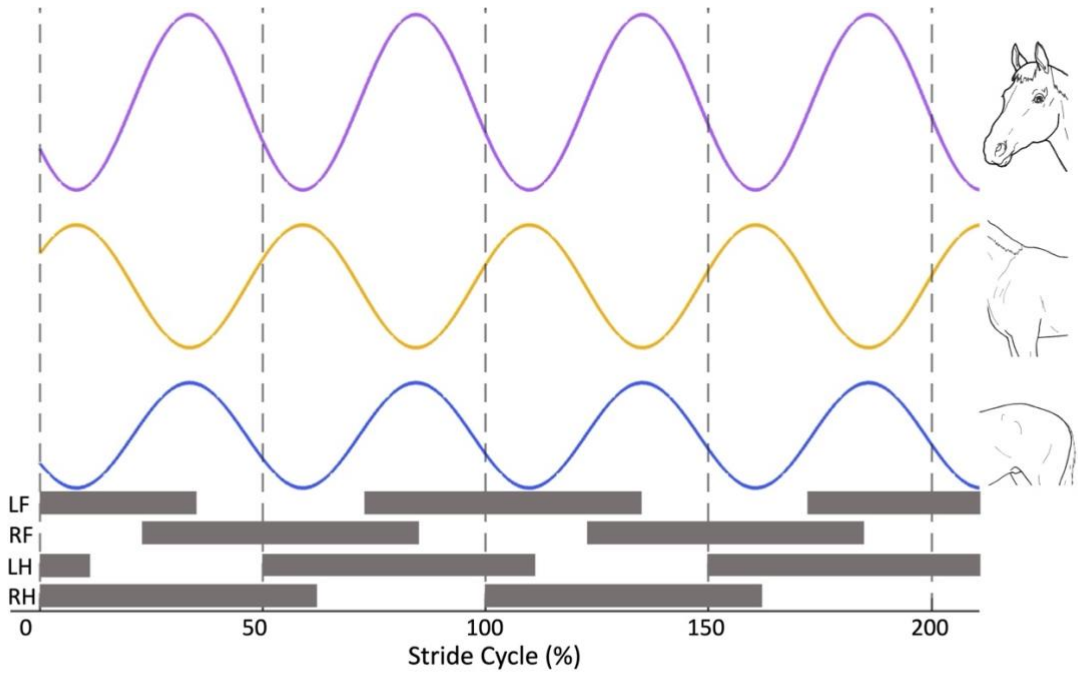


*Figure 1.6 vertical motion of poll (purple), withers (gold) and croup (blue) during two complete strides (0-200%) of the ideal, **sound walk** are shown along with relative stance durations of the four limbs (horizontal grey bars).*

1.4.2 Healthy trot stride parameters

Trot is the gait most commonly used during subjective assessments to gauge the state of lameness as the effects of lameness on many parameters are more pronounced at trot compared to walk[36]. To recognise and understand lame trot strides, it is important to first define a healthy trot.

Trot is a two-beat gait, exhibiting right-left diagonal symmetry, with bipedal support being provided by the left and right diagonal limb pairs, in turn[31]; the sequence of footfalls is shown in Fig 1.7. Periods of bipedal support may be punctuated by suspension phases, when all four limbs are off the ground. Each of the two suspension phases of the stride cycle, one following stance of the left and one stance of the right diagonal, have been reported to last 0-9% of the stride duration[31]. The duration of the suspension phase is highly dependent on a number of factors. Firstly, all temporal characteristics of stride, including moment of suspension, are known to be heavily dependent on the velocity. At walk and trot on a treadmill, increases in speed have been proven to cause a decrease in stride and stance duration, and, at a trot, an increase in the suspension phase[37]. The duration of suspension has also been reported to be affected by the level of training, elite dressage horses showing longer moments of suspension than lower-level horses[38]. Indeed, in a novice group of horses, negative values of suspension phase duration have even been reported, indicating that there was overlap in the stance phases of the two diagonal limb pairs[38]. Finally, and of particular importance to this thesis, lameness affects the suspension duration, tending to reduce the duration of the suspension phase significantly[39,40], with a total lack of suspension phase in the presence of lameness having been quite consistently reported throughout literature[25,26,41–43].

Commonly, the fore and hindlimb of the diagonal pair land and are lifted in unison at trot. When the hindlimb hoof-on proceeds that of the forelimb, the feature is named positive diagonal advanced placement[31]; when the forelimb hoof-on proceeds the hind, it is negative diagonal advanced placement. In sports training, horses are often encouraged to carry more weight on the haunches, enabling the jumping horse to lift its fore end more easily up over an obstacle and facilitating the dressage horse to achieve a higher degree of collection and more expression in the paces[44]. Thus, the horse may develop more pronounced positive advanced diagonal placement in its trot; indeed, it has previously been reported that elite dressage horses can exhibit positive advanced placements of up to 20-30ms[38,45,46] in collected trots and passage.

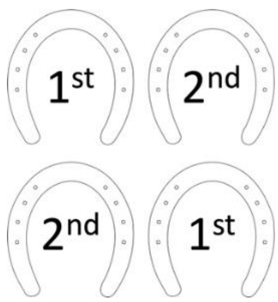


Figure 1.7 illustration of the sequence of hoof-on events for trot.

At trot, the vertical displacements of the head and trunk are biphasic[25], with the minimum vertical positions of the poll and croup coinciding with the midstance of the left and right diagonal limb pairs, sequentially. The maxima of the poll and croup occur at the moment of suspension, if there is one, where no hooves are in contact with the ground. Hoof-on events occur as the poll and croup move downwards and the hoof-off as they move up[33,34]. In the sound horse, these dorsoventral oscillations should be symmetrical within a tolerance which allows for the natural asymmetry of the horse. This conventional trot strategy for a sound horse is illustrated in Fig 1.8, which was created with reference to many literature sources which quantified relationships between vertical trunk movement and footfall sequence[25,33,34].

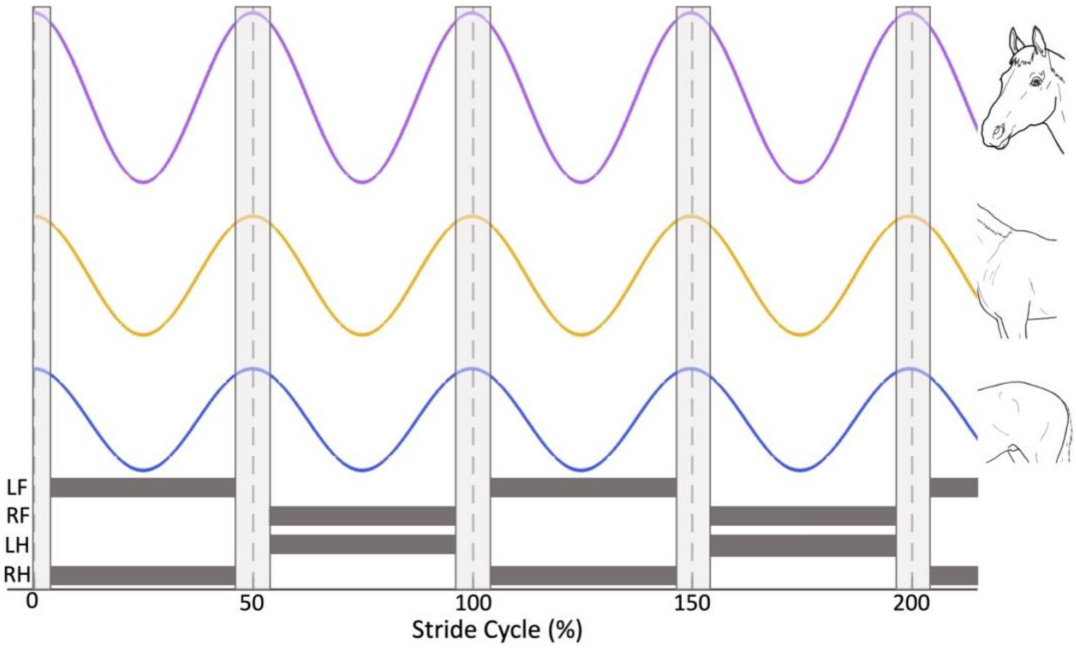


Figure 1.8 illustration of vertical motion of the poll (purple), withers (gold) and croup (blue) during two complete stride cycles (0-200%) of ***sound trot*** *are illustrated along with relative stance phases of the four limbs (horizontal grey bars) and moments of suspension (vertical grey bars), which may last 0-9%* [31] *of stride cycle.*

1.5 Lameness

Detecting the presence of lameness, classifying it and identifying the source are crucial steps for reaching a clinical diagnosis, ensuring that the most effective treatment can be selected. In this section, the alterations of gait attributable to lameness are described and explained. Lameness is characterised by deviations in gait beyond the limits of what it considered healthy and is not itself a disease.

1.5.1 Classifying lameness

Classification is an integral component of lameness assessment as it enables the clinician to plan specific and effective treatment. Lameness is commonly classified based on cause, type and source[23]. The most common cause of lameness is pain[24]; which may originate in the limbs or elsewhere in the body, for instance back pain can cause lameness[47]. Two less common lameness causes are mechanical- where the loading forces are altered by structural abnormalities in the horse's anatomy- and neurological diseases[48]. Some lameness causes pain during the stance duration of a limb (**supporting limb lameness**), and some, far less common[23] during the swing phase (**swinging limb lameness**), with combinations of the two (**mixed lameness**) also possible. Once lameness has been detected, the affected limb(s) must be identified. Fore or hindlimb **unilateral** lameness affects only one limb of the contralateral limb pair while **bilateral** lameness affects both. More complex, multi-limb lameness cases are also possible, where any combination of limbs can be affected. Previously developed methods of lameness detection, quantification and affected limb identification are discussed in detail in the subsequent chapter (Chapter 2- Literature Review).

In addition to cause, type and source, lameness can be further categorised into **primary**, **secondary** and **compensatory**. Once a gait abnormality is detected, it is important to understand which of these three it is. Primary lameness refers to the original lame limb(s) and secondary to a true lameness which occurs when a second limb becomes lame due to overloading, over time, to relieve the original source. Compensatory lameness is an apparent, false lameness where an unaffected limb may appear lame due to a weight-shifting strategy adopted by the horse to reduce loading on the primary source of pain[49,50]

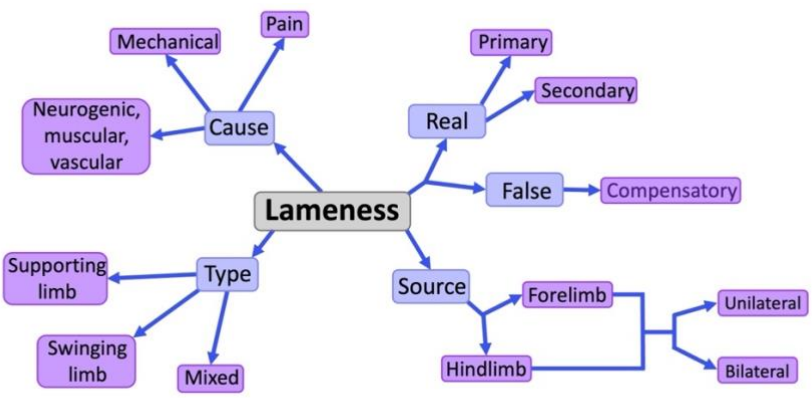


Figure 1.9 diagram illustrating some of the considerations which must be made during the classification of lameness. Some features taken from Buchner[23].

1.5.2 Effect of lameness on temporal stride parameters

Lameness induces some alterations of gait which are common to most cases. When the horse is allowed to trot overground at a self-selected speed, lameness causes a reduction in velocity[51], a shortening of the stride length and maintenance of the stride duration, with the stance durations increasing[40]. Increasing stance duration may come as a result of the decrease in velocity, as this pattern has been proven in sound horses assessed over a range of trotting speeds[37]. However, not only are the temporal parameters of gait heavily dependent on the velocity[37], the apparent degree of lameness is also affected by velocity, with mildly lame horses appearing less lame[52] and moderately lame horses more lame at higher velocities[53]. Hence, treadmills have been used to investigate the effects of lameness on temporal stride parameters at controlled speeds.

For trotting on a treadmill, lameness causes a reduction in the stride duration[36], with the absolute stance durations remaining unchanged; hence, there is an increase in the relative stance duration[51]. Lameness does not affect the left-right symmetry of stance durations at trot[51] and significant differences are likely due to individual characteristics[51]. This is in contrast to what had previously been assumed from subjective observations, that stance duration decreases with lameness as the horse hops away from the source of pain[54].

For most temporal parameters, similar changes due to lameness have been reported for fore and hindlimb cases but with far more pronounced effects in the former case[36,51]. Looking at the physiology of the forelimbs compared to the hind can help to explain this. The forelimbs have developed to be more upright and adept for load carrying than the hind, as they experience higher forces[55], supporting a higher proportion of the horse's weight (57% compared to 43%[39,56–58]). However, with the forelimbs being located closer to the horse's centre of mass[59], the effects of lameness will be more pronounced here; furthermore, using the head-neck leverage, the horse is able to have more of an influence on the left-right limb load redistribution of lameness. Additionally, some authors have suggested that the tarsal flexion of the hindlimbs[23] make them better able to damp impact forces during the gait cycle, compared to the forelimbs, and hence naturally protect more proximal structure from such loading. Thus, forelimb lameness is characterised by greater alterations to the temporal parameters compared to hindlimb lameness.

An appreciation of how lameness affects the temporal stride parameters is important for understanding how the motion of the upper body is also affected but limitations of the human eye mean that these are not the changes used to detect lameness during subjective assessments. Particularly, the temporal resolution of the human eye is reported to be in the region of 10 to 15Hz. Winter advised that measurement methods to differentiate between healthy and pathological gait should sample at least 5 times the frequency of the feature of interest. Thus, with horses trotting at frequencies around 1.5Hz[60] (step frequencies of around 3Hz[61]) the temporal resolution of the human eye would only just match the minimum sampling frequency. Considering this, it has been suggested that the human eye may not be sufficiently sensitive to detect subtle alterations of gait, particularly those associated with mild lameness[62]. For these reasons, rather than looking at the changes in temporal stride parameters, the experienced clinician will often focus on identifying asymmetries in the dorsoventral oscillations of the trunk and head. These concepts are detailed in the following sections.

1.5.3 Effect of lameness on head and trunk movement

The two oscillations of the biphasic dorsoventral head and trunk movements of the sound horse should be approximately symmetrical. In lame horses, this symmetry at trot can become significantly disturbed as the movement pattern of the horse is adjusted to reduce loading of a painful limb, minimising discomfort[33,34]. A linear relationship has been proven between the metacarpal (fetlock) joint angle and the forces experienced by the limb[63]. Furthermore, the fetlock joint angle has been cited to be a very sensitive indicator of lameness, and asymmetries in the fetlock extension of the left and right limbs of contralateral pairs has been discovered in cases of single limb lameness[64]. The ground reaction forces (GRFs) through a lame limb are known to be significantly reduced compared to the contralateral[36,65,66]. Thus, if the GRFs experienced by a lame limb are reduced, it follows that there is reduced extension of the fetlock joint angle and associated reduced vertical motion of the trunk. In this way, the reduced peak force in a lame limb is related to reduced vertical motion of the trunk. Furthermore, there is reduced propulsion from a lame diagonal which results in a lower maximum position of the trunk following push off from the lame limb. The most notable changes in dorsoventral motion are observed in the poll, in most cases of fore and many cases of hindlimb lameness, and croup for hindlimb and, less[49,67] often, forelimb lameness cases. Thus, changes in head and pelvic movement symmetry have long been used as indicators of lameness in subjective assessments[68] but improvements in quantitative gait measuring techniques have allowed the phenomena to be analysed in more detail. In the following sections, the specific effects of fore and hindlimb lameness on the poll and croup symmetry are described and explained.

1.5.3.1 Effect of unilateral forelimb lameness on poll movement

To reduce loading on a painful forelimb, the most effective strategy is for the horse to adjust the movement of the head and neck unit which accounts for approximately 10% of the total body mass[69]. Hence, the sinusoidal vertical motion of the head at trot becomes asymmetric, a phenomenon commonly referred to as the “head nod”, appearing as though the animal is nodding with alternate forelimb steps[70]. To the visual observer, it appears that the horse’s head reaches a lower minimum position during the stance phase of the sound forelimb, compared to the lame; hence the mantra “down on sound” can be used to help identify a lame forelimb. Various strategies have been proposed to describe the way vertical poll motion is adapted to alleviate pain associated with forelimb lameness[25,34,71–73]; common to all these strategies is reduced vertical poll motion during the stance phase of the lame forelimb which may be accompanied by a compensatory increase in vertical poll motion during stance of the contralateral healthy limb. One study investigated the correlation between vertical poll motion and GRFs recorded using a force plate[74], finding that differences in peak vertical force between the stance of right and left forelimbs could be predicted using vertical motion of the poll with a standard error of 6.1% (when vertical head movement asymmetry was used) and 5.2% (when vector sum was used). Hence, not only is the vertical motion of the poll related to the GRFs of the forelimbs, but it can also even be reliably used to predict the GRFs and, hence, identify unilateral or unilateral-dominant lameness.

After scrutiny of the literature[29,71,73,75–77], Fig 1.10 has been created to illustrate the alteration of poll motion with lameness; approximate timings of the stance phases of the lame and contralateral limbs are indicated by vertical panels. Generally, alterations of poll motion with lameness can be understood as the horse holding their head elevated at the midstance of the lame limb, compared to the contralateral, to relieve loading, and not reaching as high a maximum position following push-off from the lame limb as there is reduced vertical propulsion.

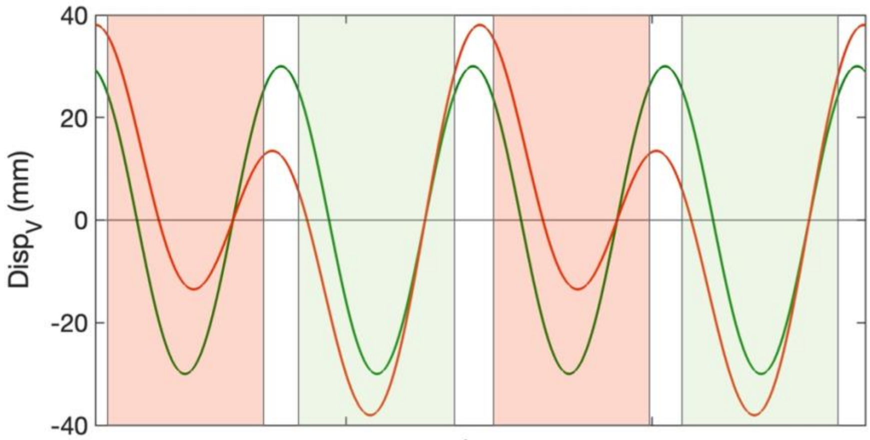


Figure 1.10 illustration of alterations of vertical poll or croup motion with unilateral lameness. Two stride cycles of hypothetical vertical poll or croup displacement (Disp$_V$) are represented for sound (green line) and unilaterally lame (red line) gait. Stance phases of the lame and sound limbs are illuastrated (red and green vertical bars, respectively). Details taken from literature[29,71,73,75–77].

1.5.3.2 Effect of unilateral hindlimb lameness on croup movement

In cases of hindlimb lameness, the usually symmetric movement of the croup at trot is adjusted, becoming asymmetric, to reduce loading on a painful limb, a phenomenon referred to as "hip hike"[24]. Subjectively, clinicians may look to detect asymmetry in the rotational motion of the pelvis at trot, by observing the relative motion of the tubera coxae, where the tuber coxae on the lame side might be seen to increase in vertical displacement relative to that of the contralateral[78]. When objective methods are used, the vertical displacement of the croup can be measured and asymmetries detected as an indication of hindlimb lameness. Different strategies of vertical croup motion, to accommodate hindlimb lameness, have been proposed[33,71,72].

Similarly to poll motion in cases of forelimb lameness, changes to the croup motion can be understood by considering the relationship between the ground reaction forces and the vertical trunk motion[79], in particular the association between peak force and fetlock drop (angle) of the lame limb. With the fetlock angle being linearly related to the force experienced by the distal limb[63], the reduction in peak force in the lame limb at midstance will result in a reduced fetlock drop. Hence, there will be a reduced vertical range of motion of the entire hindlimb linkage, including the croup. As there is reduced push-off from a lame diagonal, the croup will tend not to travel as far upwards vertically compared to after push-off from the healthy diagonal, and thus there will be a reduced range of vertical motion. However, the absolute maxima reached may still be higher than after push-off from the healthy diagonal as the absolute minima was also not as low. One study, which compared the vertical pelvic motion to the vertical and horizontal GRFs measured by a force plate for horses at trot[80], found that the difference in maximum pelvic displacement measured in consecutive steps of the stride cycle were strongly correlated with a transfer of vertical to horizontal force impulse during the second half of stance. There was also a moderate association between the minimum pelvic displacement and difference in peak vertical GRF. Thus, the vertical croup motion has been proven to be representative of the GRFs experienced by the hindlimbs.

After extensive examination of the literature, this concept is illustrated in Fig 1.10 which demonstrates changes in vertical croup motion at trot with the introduction of unilateral hindlimb lameness, where the stance phases of the lame hindlimb is illustrated by red bars.

1.5.3.3 Compensatory lameness

Identifying the source of lameness can further be confounded by the presence of compensatory lameness[49,67,81,82]. This is a false lameness which arises in response to a true, primary lameness when the horse adjusts its movement, to relieve loading from the source of pain, in such a way as it appears lame in another, healthy limb. During lameness assessments, it is important to consider the possibility of compensatory lameness to avoid misidentification of the source of lameness. Moderate to severe unilateral forelimb lameness has been found to induce compensatory lameness in the hindlimbs[81,83]; this most commonly manifests as apparent lameness of the contralateral hindlimb[49] and possibly some mixed lameness[84]. Far more commonly[49,67], primary unilateral hindlimb lameness has been reported to induce compensatory lameness of the ipsilateral forelimb[82]. Indeed, induction of mild lameness in a hindlimb has been reported to instigate a more severe, false lameness of the ipsilateral forelimb[83]. The severity of compensatory lameness varies between horses, with the same degree of induced primary lameness causing very limited changes in the head movement for some horses and dramatic asymmetry in others; it is believed that the mechanics of compensatory lameness are heavily dependent on the horse's conformation and is suggested that this should be considered a confounding variable when assessing compensatory lameness[83].

Some authors have proposed that differentiation between true and compensatory lameness can be achieved by quantifying the vertical excursions of the withers[71], which also become asymmetric with lameness. In the presence of true forelimb lameness, during the stance of the lame diagonal (diagonal limb pair in which lame limb presides), both head and withers are expected to reach a higher minimum position compared to during stance phase of the healthy diagonal limb pair. In contrast, in presence of true hindlimb lameness, the withers and croup are expected to reach a higher minimum position during stance phase of the lame diagonal, compared to during that of the sound, but the head is expected to behave in the opposite way, reaching a lower minimum position during the lame diagonal stance compared to the sound.

1.6 Conclusion

Thus, the healthy gait patterns at walk and trot have been described; parameters and terminology which will be used throughout this thesis have been defined, and previously described manifestations of lameness have been illustrated. In the following chapters, some of these phenomena will be explored using quantitative methods.

Chapter 2 Literature Review

2.1 Lameness

Lameness is a clinical sign and not, in itself, a disease[23,24]. Lameness is the most common component of the equine clinicians workload, accounting for up to 40% of working time[85] and has consistently proven to pose the heaviest economic burden to the equine industry, in terms of mortality rates, training days lost, as well as the cost of veterinary interventions, drugs and additional therapies[3–5]. The issue of lameness is endemic, having been found to be the most common problem affecting populations of young racehorses[19]; elite and non-elite dressage horses[8]; older horses[6]; and in cross-sections of national herds[7,9]. In the following sections of this chapter, the subjective lameness examination and objective lameness detection methods, including tool options for gait quantification, are presented and reviewed. Literature in the area of quantitative lameness detection is summarised and the limitations of current practices highlighted.

2.2 Assessment of lameness

2.2.1 Subjective lameness assessment

Traditional lameness examinations (sometimes called lameness workups), composed of visual and tactile tests by the veterinarian, are used to investigate poor performance in horses and are routine in many pre-purchase vettings. Traditionally, lameness has been defined as any alteration in gait attributable to a disorder in the structure or functionality of the locomotor system[86] and can also manifest as a change in behaviour, attitude, or performance. These abnormalities can be caused by pain originating from many body locations including the neck, back, limbs or hooves, and identifying the source is imperative to appropriate treatment selection. Several steps are common to many subjective lameness examinations:

- **Medical history**- owner/handler provides details of horse's past and present health and any changes in performance.

- **Visual appraisal at rest**- conformation, balance and weight-bearing are assessed and signs of obvious disease or injury looked for at rest.
- **Physical examination**- palpation of the skin above muscles, joints, bones and tendons, checking for signs of pain, heat, swelling or other physical abnormality.
- **Evaluation in motion**- the horse is walked and trotted in-hand on at least one firm, level surface in front of the clinician who looks for deviations from healthy gait, principally: failure to land squarely or unnatural shifting of the weight away from particular limb(s). This is the stage where the incorporation of quantitative gait analysis is most beneficial.
- **Joint flexion test**- the limb is held in a flexed position for a duration; when the limb is released, the horse is immediately trotted away and the veterinarian looks for alterations and irregularities of gait which are characteristic of lameness. Flexing the joints thus can apply pressure or stress to a specific anatomical region of the limb which some argue causes a short-term, transient exacerbation of pain in the region, allowing problems to be detected which may not be visible without the flexion test. Thus, the test facilitates the clinician in identifying subclinical issues or recognising the origin of lameness, although the usefulness of flexion tests in subjective evaluations is debated, with research suggesting that the interpretation of their effect is inherently subjective, with considerable between-observer variation[87,88]. In quantitative studies, the usefulness of flexion tests has been proven as a positive response to such tests induced significant changes to objective measurements of pelvic symmetry[87].

After each stage of motion analysis, lameness is typically graded on a scale which can be either categorical or numerical, with research proving that the two approaches should not be used interchangeably[89]. The UK scale ranging from 0-10, (where 0 is non-lame and 10 is non-weight-bearing lame, but with no definitions of the intermediate points on the scale) and AAEP scale (ranging from 0-5) are two such numerical scales[90,91]. The AAEP scale, which has come under criticism for not allowing grading of lameness independently under different conditions[92] (for example during walk or trot, and on a straight-line or circling,) is broken down as follows:

- 0: Lameness not perceptible under any circumstances.
- 1: Lameness difficult to observe and not consistently apparent, regardless of circumstances and test conditions.
- 2: Lameness difficult to observe at walk or trot in a straight-line but consistently apparent under certain circumstances for examples when the horse is exercised on a circle, on an incline, on a hard surface or under saddle.
- 3: Lameness consistently observable at trot under all circumstances.
- 4: Lameness obvious at walk.
- 5: Lameness produces minimal weight bearing in motion and/or at rest or a complete inability to move.

When testing the horse in motion, the clinician looks for clinical signs such as shortening or irregularity in stride length, irregular hoof placement, signs of stiffness or the features of head nod or hip hike which can be symptomatic of lameness. During assessments, the veterinarian is often limited in terms of what conditions they can test the horse under by the availability of facilities, as lameness workups are often carried out on location, where the horse is kept. As a minimum, clinicians assess the horse at walk and trot in straight lines on a firm surface, as this often yields the most information[93]. If location allows, they may also wish to see the horse exercised in circles on the lunge line as circling can accentuate the appearance of some low-grade lameness cases[29,62,94,95]. Often, it can also be beneficial for the horse to be assessed on additional surfaces as different surface firmnesses may accentuate different lameness cases[29,95,96]. For instance, joint and bone related issues such as arthritis may be more evident on hard surfaces like asphalt, while soft tissue injuries, such as tendon damage, might be most obvious on soft surfaces, such as sand[97]. However, there is currently no quantitative data available to support the use of different surface firmnesses to discriminate between causes of lameness[98].

Following the initial examination, analgesic nerve and/or joint blocks may be used to identify the source and probable cause of lameness. Working systematically, the clinician delivers localised doses of analgesia to increasingly proximal locations of the body, starting with the most distal possible source of lameness, which causes temporary numbing of the area. The visual examination is repeated after each drug delivery; the rationale is that when the source of pain is treated, sound gait will be temporarily restored. Thus, analgesic blocks facilitate the clinician in identifying the source of lameness. Although nerve blocks are a mainstay of current practice, when used in conjunction with subjective assessments alone, some caution should be exercised as there have been reports of bias in the interpretation of their effects[99,100]. In contrast, there are an increasing number of publications which report the reliable use of nerve blocks for lameness detection and characterisation, when used alongside objective methods, finding that such methods are able to detect positive responses to nerve blocks[101–104].

While subjective routines remain the most common method for lameness assessment, there are widely reported limitations of the practice to detect lameness. Poor inter-observer agreement is very common for all grades of lameness, with clinicians disagreeing on the grade of lameness and the most severely affected limb[62,89,105,106]. Although intra-observer agreement tends to be higher[107], in cases of mild lameness poor intra-observer agreement has even been reported, with the same clinician giving a different assessment when asked to re-examine the same horse in the same lameness condition[108]. Lameness is commonly detected by virtue of the asymmetric motion it induces in horses at trot. Further to issues of poor inter- and intra-observer agreement, the results of another study suggest that human sight may be insufficient for detecting the subtle asymmetries which are sometimes the only indication of lameness[109]. As discussed in an earlier section (1.5.2 Effect of lameness on temporal stride parameters), the human eye may have too low a temporal resolution for detecting the subtle and complex movement patterns which are characteristic of some, particularly mild, cases of lameness[62].

The significant issues associated with the visual appraisal of lameness have given rise to the development of quantitative methods; these are discussed subsequently.

***Summary**: whilst visual methods of lameness assessment remain the most commonly used in clinic, the significant limitations of these methods, especially for identifying mild cases of lameness, justify efforts to develop comprehensive quantitative tools for lameness detection.*

2.2.2 Instrumented lameness assessment

Objective methods to assess lameness usually incorporate a trot-up, like that of subjective assessments, with the addition of systems to quantitatively measure aspects of gait. Once data has been collected, analysis for detection of lameness in the spontaneously lame horse can broadly be approached in two ways[23]; which of these is chosen is worth consideration as they have a bearing on how methods of lameness detection and quantification can be applied[110].

The first approach compares values to those of a 'standard horse'. Threshold values are established to differentiate between lame and sound groups based on values obtained from a cohort of sound horses which should be representative of the natural variation which might be expected in a larger population of sound horses. However, this approach can be problematic as the natural biological variation seen in a healthy horse, especially in terms of movement symmetry, can often be greater than the degree of change due to lameness in another horse[111,112]. For instance, a young sound horse might naturally demonstrate a higher degree of asymmetry than a more established horse suffering unilateral lameness[113]. However, there is increasing literature[72,98,114,115] available which has assessed the movement symmetry of sound populations, under different conditions (such as straight lines and circling), which can advise on discriminating between asymmetries due to lameness and those due to natural sidedness.

Many parameters, especially temporal stride parameters such as stride and stance duration, are highly correlated with the horse's signalment so correction factors may need to be made to account for the horse's height, for example. Not only this, but such parameters are also heavily dependent on velocity. At walk and trot on a treadmill, increases in speed have been proven to cause a decrease in stride and stance duration, and, at a trot, an increase in the suspension phase, while having no effect on the upper body motion symmetry in sound horses[37]. In lame horses, the latter features have been found to be only slightly and inconsistently affected by velocity[52]. Thus, for comparison with the standard horse, the velocity of the horse must be carefully considered.

The second approach compares values obtained for the lame horse to those obtained from the same horse in a sound state. A key benefit of this is that the horse is used as its own control, getting around the issues raised by the first approach related to inter-individual gait variation in horses and signalment influencing the parameters.

The control data, with the horse measured in a sound state, can be achieved in two ways. The data may be compared to baseline readings taken from the same horse before the onset of lameness which is useful in a research setting, where lameness could be artificially induced, but has limited use in everyday clinical applications as it is unrealistic to assume data will be collected prior to the onset of spontaneous lameness, especially as horses are often presented for gait analysis only after lameness is apparent or there is an effect on performance.

Alternatively, the horse may be assessed before and after the administration of analgesic nerve blocks[104]. This method assumes that nerve blocks temporarily relieve pain caused by a pathology and thus reverse the gait pattern to a sound, pre-lameness state and is used extensively in both subjective and objective lameness assessments. A number of early papers debated the usefulness of nerve blocks for this application, being conflicted as to whether reversing the effects of lameness in lame horses was the only effect of such practices[116–118]. However, in more recent times, an increasing number of publications report on the reliable use of nerve blocks, for lameness assessment, with quantitative gait analysis methods used before and after analgesia delivery, finding that such methods are able to detect positive responses to nerve blocks[101–103]. One minor drawback to this approach could be the need for recording at least two sets of data- before and after nerve blocks- making the process perhaps more time-consuming than the first approach suggested. However, given that nerve blocks are a mainstay of clinical lameness workups, it is perhaps unlikely that this would be a deterrent for using the methods in the clinical setting. As many temporal stride parameters, especially stride duration and length[119], are highly dependent on speed, these methods are only valid if the horse's speed is controlled before and after nerve blocking. Thus, additional equipment such as a treadmill or light gates to assist the handler in controlling the speed, may be necessary which could be a barrier to integration into some clinical practices. However, as speed has been reported to cause only slight and inconsistent alterations to upper body motion symmetry[52], one of the most important signifiers of lameness[25,36,73,76], this is unlikely to be totally prohibitive.

Summary*: when quantitative methods are used to establish the presence of lameness, test data collected from the affected horse can either be compared to that of the standard horse or to that of the same horse after diagnostic analgesia.*

Quantitative gait analysis methods can loosely be divided into two categories: those based on kinetic features of gait, and those based on kinematic features. The kinetic approach is concerned with the internal and external forces resulting from musculoskeletal work, analysing the relationship between the forces and the changes it produces on the body. Hence, these methods use tools which measure the forces exerted by the body either directly (as in the case of force plates) or indirectly (as with pressure plates)[120]. The kinematic approach concentrates on the geometric and time-dependent aspects of motion; displacement, velocity and acceleration of body segments, as functions of time, relative to a reference coordinate system are studied. Thus, the kinematic approach makes use of tools which measure time-dependent aspects of motion, for example displacement (as with optical motion capture) or linear accelerations (as with accelerometers). Many measuring systems are available to quantify aspects of equine gait, each have pros and cons, which are discussed subsequently, and choosing suitable equipment should be decided based on, amongst other factors, the aims of the analysis and the conditions under which data will be collected. Some examples of different gait analysis systems are presented in Fig 2.1.

Figure 2.1 Collage of five gait analysis systems. Images adapted from literature and trials recorded for the present study. Examples of IMUs (photo taken from trials), instrumented horseshoe[121], hoof pressure device (Tekscan, South Boston), OMC (Qualysis, Göteborg) and force plate[122] are shown.

Force plates use transducers to measure the force applied to their surface, in a three-dimensional Cartesian coordinate system, at the point of application- centre of force (CoF). They can be classified based on the transducers used; strain gauges, capacitance gauges and piezo-electric or -resistive sensors being some of the common components. Force platforms were used in some of the earliest attempts to quantify equine lameness[123–126], as they can record the redistribution of loading away from a lame limb. Force plates are the gold-standard of weight-bearing lameness detection due to their high accuracy and precision for measuring GRFs[127], they are usually also programmable up to very high sampling frequencies. They can be used to detect subclinical injuries, before lameness becomes apparent[128], can be used to measure disease-specific changes in GRFs, such as those associated with navicular disease[129], and can even be used detect cases of bilateral lameness[74],. However, data collection can be laborious and highly time-consuming, as the number of strides analysed is limited by the area covered by force plates and, hence, the number of force plates available to measure strides. Furthermore, the horse is required to place a single hoof completely on the force plate for a correct measure of GRF to be recorded. When the number of force plates is limited such that only one stride can be recorded, stride-to-stride kinetic variations due to lameness cannot be analysed[102]. Finally, although a handful of papers have now used force plates under field conditions[130,131], they are generally limited to use in the most highly advanced equine gait analysis laboratories.

Another drawback of force plates is that they are only able to measure the total GRF at the CoF and do not indicate how the force is distributed across the whole solar surface. **Pressure plates and mats** have been developed to overcome this limitation and have the additional benefit of being able to record several consecutive strides if the plate is large enough. Like force plates, they use devices of resistive or capacitive sensing technology, here to measure the pressure distribution across the load-applying surface. Thus, force distribution across the solar surface can be indirectly measured. These devices are advantageous when force distribution across the heel, quarters and toe is of interest, such as when aspects of farriery and hoof balance are investigated. Some studies have used pressure plates to evaluate gait on different surfaces, by covering the pressure plate with a rubberised surface and recording data with and without the addition of sand and synthetic fibres[132]. However, as with force plates, the number of strides analysed will be limited by the area covered by the measuring device and data collection can be onerous. In one study, researchers found that 13±1 walk and 19±7 trot trials had to be recorded for each pony to ensure five valid measurements of both forelimbs were recorded using a standalone pressure plate[133]. Data from pressure plates cannot be used to decompose the GRF into three directions, they are also neither as accurate nor precise as force plates[134], meaning that they cannot currently be used as a direct alternative. Previous studies have also cited that the accuracy of pressure plates can be suboptimal for quantifying equine gait without calibration using a force plate, especially during the impact and breakover phases of the gait cycle where the loading of some sensing cells may not exceed threshold values[135].

The issue of limited strides for analysis has previously been resolved by the development of **instrumented treadmills**, featuring force plates positioned under the treadmill belt to measure the GRFs of consecutive loading of all four limbs[136,137]. While these offer the opportunity to record an unlimited number of strides and can be used to assess horses at any speed and gait, even up to full gallop, they come at very high purchase costs which preclude them from widespread daily clinical use and means they are restricted to the most well-equipped gait laboratories. Indeed, one group of authors deemed the treadmill designed by Weishaupt et al.[136] to be "rather complex and unwieldy" and that it "would be difficult to apply except in a lab situation"[102]. Treadmills are also limited in terms of the conditions under which data can be collected, only allowing gait assessment in straight lines and on a single surface type- the belt. In practice, exercise in a circle and on different surfaces can be highly informative for lameness workups and performance assessments. Treadmill belts are usually of toughened rubber, although different compliances are available[138]. Furthermore, horses require habituation to treadmills[139–141] and some previous studies have indicated that there may be significant differences between equine locomotion overground compared to on a treadmill[137,142,143]. Therefore, while instrumented treadmills are a very valuable tool for use in research settings, they are currently not convenient for use in the daily clinical environment.

As early as 1958, there were efforts to develop wearable systems for measuring GRFs between the horse's hoof and ground[144], the benefits of which are evident- multiple strides can be recorded, overground and under different exercise conditions, including on different surfaces. However, these concepts were not developed further until the 1990s, when a comparative study was used to validate a **force-measuring horseshoe** against a static force plate[145]. The horseshoe was found to record force traces similar to those measured by the force plate and there was a strong linear relationship between the force applied and the sensor signals, indicating that the instrumented horseshoe may be developed as a means of accurately recording the GRFs. However, authors cited issues with the calibration of the device. Since, instrumented horseshoes based on strain gauges[146] and piezoelectric sensors[147,148] have been developed to measure GRFs in three dimensions at the POF and these proved suitable for tests under racing conditions where they were used to investigate the effect of different track surfaces on GRFs[147]. In a more recent publications, a dynamometric horseshoe has been successfully used by one group to investigate the peak vertical forces of the inside and outside hooves of horses walking, trotting and cantering on a circle[149] and to compare loading on the superficial digital flexor tendon at walk and trot on asphalt and sand[150].

Although these devices might be useful for recording data over long distances and in a variety of different surface conditions, offering an immediate advantage over force or pressure plates, they also have many significant disadvantages. The devices are based on metal shoes and must be attached using conventional shoeing techniques, meaning attachment is a lengthy and involved procedure. Furthermore, as with other metal shoes, they must be replaced when worn and different shoes would be needed for each horse unless horses are screened to ensure they have similar sized and shaped hooves[146]. Instrumented horseshoes can be heavy and cumbersome, limiting their clinical applicability[127]. Some authors have highlighted difficulties with fabricating instrumented horseshoes and that the added size and weight they introduce to the horse's distal limb might have a significant effect on the horse's gait, making them unsuitable for data recordings which intend to imitate real world scenarios[102]. The author of this thesis also suggests that shoe design might have an additional effect on gait, by lifting the horse's hoof such that it no longer meets the ground which will undoubtedly have an impact on the physiological function of the hoof. Thus, although instrumented horseshoes pose an interesting avenue for research applications, they are currently unsuitable for clinical use.

Wearable **hoof pressure sensors** have been developed from the in-shoe pressure measuring devices that are now popular in human locomotion studies[151,152]. Mapping the pressures beneath the hoof using piezoresistive sensing technology, they are particularly useful when information is needed about the distribution of load over the solar surface and, as with pressure mats, could be especially desirable for studies concerned with different farriery techniques and hoof-balance applications. These devices can be relatively lightweight and collect data to a datalogger attached to the horse, making them practical for use on different exercise surfaces and over long distances. In studies by one group, such devices were used simultaneously between the hoof and shoe, and between the shoe and ground to assess the effects of different shoeing conditions (barefoot, with standard horseshoes and with various different therapeutic horseshoes) on the solar pressure distribution recorded on several surfaces (concrete, rubber matting, firm and soft sand)[153–155].

Although these users had great success using the devices, nailing the first between the hoof and shoe and taping the second to the bottom of the shoe, others have cited difficulties with attachment as being a major limitation, finding the most successful solution to be trimming the sensor to the correct shape for the individual hoof and securing to the hoof with a glue-on shoe[156–158]. Thus, attachment is time consuming, with the glue needing time to cure, and requires a certified farrier to fit the shoe correctly. The datalogger poses an additional inconvenience compared to some alternative systems, as it must be attached to the horse. In a recent reliability study, one of the most popular hoof pressure systems (Tekscan Hoof System, Tekscan, Boston, MA) was found to be reliable within-sessions but not between-sessions[156] it was discovered that creases in the sensors caused areas of high stress which damaged the sensing cells, resulting in unreliable readings or areas which did not register load at all. Furthermore, sand from the exercise surface and moisture caused delamination of sensors. Hence, while wearable pressure measuring devices might appear to be a convenient alternative to other pressure and force measuring systems, substantial developments are necessary before they can be relied upon in the wide-ranging conditions under which horses are exercised and tested.

Since its conception, serial photography has been used to capture equine gait. From Marey's Animal Mechanism[159] and Muybridge's The Horse in Motion[160], advancements in photographic technology have led advancements in equine gait analysis. In the modern day, high-speed video cameras are used to study equine locomotion with the current state-of-the-art in video based gait analysis being three-dimensional (3D) marker based **optical motion capture** (OMC). Reflective markers are attached to the skin above the body regions of interest and a system of infra-red cameras, erected around a calibrated capture volume, track the markers in 3D space.

The data captured allows the researcher to explore the linear and angular displacements of the body segments. Due to their very high accuracy and precision for measuring displacements, such systems are considered the gold standard in kinematic analysis[161].

However, there are significant practical limitations of OMC. The high purchase cost of systems means they are mostly the preserve of well-equipped research facilities and, thus, not convenient for daily clinical applications. The number of strides which can be recorded and analysed is limited by the size of the capture volume, which is determined by the number of cameras available, a problem some authors have overcome by recording gait on a treadmill but this incurs the limitations associated with treadmills discussed previously[139–141]. To overcome issues of limited field of view, systems of up to sixty cameras which can be used indoor or out have been developed, enabling data capture over very large areas (Qualisys, Göteborg, Sweden), meaning that horses can be assessed in environments more like their daily exercise or living conditions than the gait laboratory but still precludes data collection at any site. The validity of OMC can also suffer as a result of marker occlusion, for instance when markers become obscured by a rider[162,163] or handler[76]. Furthermore, methods of OMC can be affected by displacement of the skin relative to the landmarks beneath, the motion of which they are supposed to represent[164]. The relative contribution of these 'skin artefacts' is highly dependent on the location at which a marker is attached, being almost negligible in the region of the distal limbs, where there is minimal soft tissue, but substantial in other more proximal areas[165,166]. In studies comparing the same horse to itself over time or to horses of similar size and morphology, the effect of skin artefacts may be overlooked as horses will be similarly affected and in studies where the skin artefact cannot be neglected, for instance when the absolute displacement of specific landmarks is essential, several subject- and task-specific correction algorithms for equine locomotion have been developed[167,168]. More simply, a suitable filter, for example a low pass Butterworth filter[169], may be applied to the data to remove soft tissue artefacts.

Despite these advancements, the post-processing involved in the use of OMC can be time-consuming which, along with the practical limitations of the hardware, means that it is not always a convenient means of gait quantification in equine studies.

Wearable inertial measurement units (IMUs) have become increasingly popular in equine research[170] and have been heralded as a convenient means of gait quantification, overcoming many of the limitations associated with other systems. These sensors can contain various kinematic measuring components, from the most basic housing only a single-axis gyroscope or accelerometer, to the more sophisticated containing triaxial accelerometers, gyroscopes and magnetometers. The flexibility of different device configurations has been driven by developments in microelectromechanical systems[171]. IMUs popularly used for gait analysis often contain triaxial accelerometers, which measure linear accelerations in 3D, triaxial gyroscopes that measure the angular velocities and triaxial magnetometers which detect magnetic field intensity. When the data from these three sensors are mathematically fused, the Euler angles can be calculated and, hence, the orientation of the device at different time points during data recording can be determined[172,173]. Modern IMUs are lightweight and wireless, commonly having both an on-board secure digital (SD) card for local data storage and Bluetooth capabilities such that data streams can be transmitted wirelessly in real-time to a nearby computer. Fig 2.2 illustrates the increasing popularity of sensor based gait analysis in equine studies.

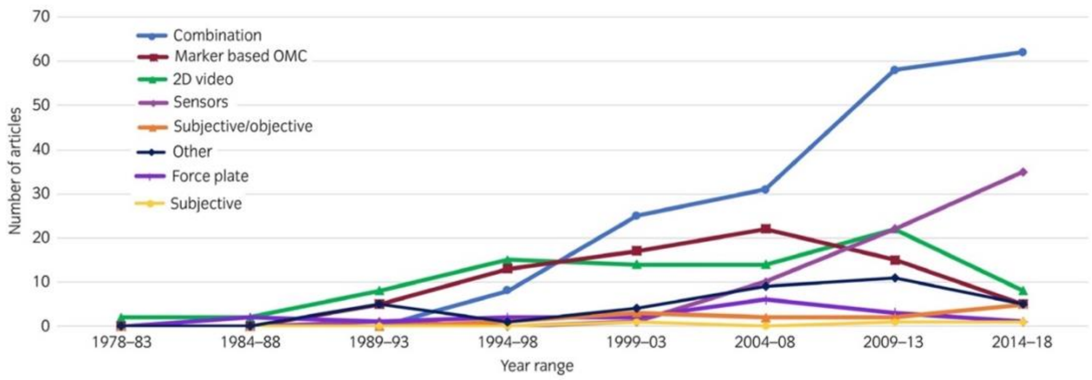


Figure 2.2 Illustration of research trends in equine biomechanics. The choice of gait analysis techniques in a sample of 510 research manuscripts published between 1978-2018 are illustrated; adapted from Egan et al.[170].

Accelerometer-containing IMUs are perfectly suite to investigating hoof accelerations and, thus, the GRFs and impacts experienced by the hooves. The early uses of hoof-mounted accelerometers used the devices to investigated the GRFs and the effects of different surfaces on these at walk, trot and canter[174,175]. More recently, hoof-mounted devices have been used to measure the hoof accelerations with different shoeing conditions and different surfaces[176].

So convenient are IMUs, that a majority of the most popular commercially available systems for equine gait analysis are based on the technology (EquiGait, EquiGait Ltd., Herts, UK; EquiMoves, Uthrecht, The Netherlands; Lameness Locator, Equinosis Q, Columbia, USA). In a survey of seventy-two clinicians, 55% of forty users of quantitative systems used the most popular[161], consisting of head and pelvic accelerometers and a single-axis gyroscope attached to the right fore pastern (Lameness Locator).

Methods of double integration specifically for equine gait analysis have been developed and validated which enable linear velocities and displacements to be calculated from IMU recorded data[76,77,177]. These have been proven to yield highly accurate quantifications of displacement, when compared to the results of OMC systems, with one method yielding median(25th, 75th percentile) accuracies of 0.1(-9.7, 10.8)mm in the x-, -3.8(-15.5, 13.7)mm in the y- and -0.1(-6.3, 7.1)cm in the z-direction[177]. When this method was integrated into a commercial system, authors reported achieving comparable mean biases of within ±5mm for quantifying symmetry indices[76]. Despite these successes, the process of double integration can nonetheless be difficult to implement and prone to significant error. The drift incurred by gyroscopes which can accumulate over time, making the instrument less accurate as data collection progresses, can be a significant problem as the errors it introduces are magnified at each stage of integration. However, methods are available which aim to minimise the effect of these errors, including regular resetting of the gyroscope during data collection, applications of specific filters[178,179], inclusion of attitude and heading reference systems or methods which use the output of the accelerometer to mathematically correct gyroscopic drift[180]. When data collection is performed outside, accuracy can also be improved by the incorporation of a global positioning system (GPS)[181] but these are less useful in areas where GPS coverage might be obstructed, for instance by dense tree coverage. As with OMC, these systems can also suffer the effects of skin artefacts[182], caused by displacement of the sensor and underlying skin with respect to the bone[183], although these have not been as heavily researched as for OMC markers[182]. Indeed, the soft tissue artefact associated with IMUs might be expected to be greater than that affecting OMC markers, as IMUs are much larger and heavier. The natural frequency of a skin artefact has previously been proven to be inversely related to the mass of the device and its holder[182] while the oscillation duration is expected to increase linearly with increasing sensor mass[184]. As with OMC markers, the magnitude of such artefacts will be dependent on the location where the sensors are mounted[185], being comparatively small in areas where there is minimal or no soft tissue, such as on at the distal limbs and hooves, but in some more proximal areas, where there is a lot of soft tissue, these artefacts are expected to be much greater[165,166].

The flexibility offered by the IMUs, along with their relatively low cost compared to OMC alternatives, make them an ideal solution for data collection under field conditions; indeed, in human studies, they are also being regarded as the solution to data collection in clinical settings[186]. IMUs can be used to record data in many different test conditions, on any surface and over any distance[161]. For equine gait analysis, they are convenient as they can be attached to various locations on the horse using non-invasive attachment methods, such as tape or sticky-back hook-and-loop fasteners. Thus, attachment is relatively straightforward and set-up times are kept to a minimum which is particularly important when dealing with equine subjects who may become bored and agitated during lengthy instrumentation routines. The sensors are also far less cumbersome than some other available systems (such as on-hoof pressure devices or dynamometric horseshoes) meaning that they have minimal impact on the horse's natural gait and behaviour[187].

Owing to the advantages they offer over the alternatives, IMUs were the devices of choice throughout this thesis. The system used was developed by Shimmer Sensing, (Dublin, Ireland). Devices contained triaxial accelerometers, gyroscopes and magnetometers and these internal components were calibrated using a predefined protocol (9DoF Calibration Application User Manual Rev 2.10a) and software provided by the manufacturer (Internal Shimmer 9DOF Calibration; Internal Shimmer

9DOF Calibration (200g Support)). The default directions of the axes of the components within the Shimmer IMUs are illustrated (Fig 2.3).

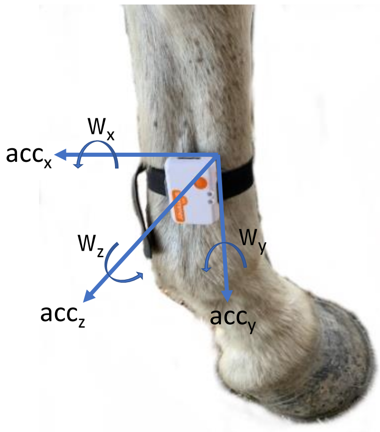


Figure 2.3 Illustration of the Shimmer IMU axes directions. Accelerations are in the x-, y- and z-directions (acc_x, acc_y and acc_z) and angular velocities about the x-, y- and z-axes (ω_x, ω_y and ω_z). In this example, the IMU is attached to the cannon of the right forelimb.

***Summary**: many different tools are available for collection of quantitative gait data, all have their respective pros and cons. The characteristics of IMUs make them a convenient choice for data collection under a variety of field conditions.*

2.3 Gait Event Detection

Many of the methods of objective gait analysis and lameness detection which will be discussed in the subsequent sections of this chapter are reliant on the reliable segmentation of data into periods of stride durations[177,188]. This can be achieved by accurate determination of the timing of gait events which characterise the stride cycles. Furthermore, accurate detection of the gait events, hoof-on and hoof-off, are essential for calculation of the stance and swing durations of the stride. Impairment of the suspension phase of trot can be the first clinical indication of lameness[39] and, as such, it is essential that the hoof-on and -off events can be accurately and reliably detected to calculate this parameter.

The gold standard of event detection uses force plates to directly measure the moment at which the limb is loaded and unloaded[127]. However, as discussed, use of force plates is not convenient for clinical applications or for measuring outside the laboratory. Therefore, several alternative methods have been developed and explored.

Methods which use OMC data to detect the gait events have been validated and found to be accurate and precise for measuring the stance duration of horses, when compared to force plate methods [115,188–190]. However, not only are OMC based methods often limited to the laboratory, but they can also incur losses of accuracy due to marker occlusion; in particular, markers attached to the hooves may become occluded when the horse moves on sand. Some researchers have overcome such limitations by using a 'marker wand' (a rigid device of orthogonal members to which markers are attached)[17,177,191] but this could add additional complexity to the experimental setup. For these reasons, along with the limitations of OMC systems discussed previously, methods of gait event detection based on IMU data might be more widely applicable.

Olsen et al.[192] attached IMUs to the distal limbs and along the trunk midline to explore different methods of gait event detection at walk. These were based on feature extraction, namely peak detection, of the obtained accelerations and derived displacement signals. Attachment to the metacarpals and -tarsals yielded more accurate and precise detection of gait events than attachment to the upper body locations, although they found that a sacrum mounted sensor detected the hindlimb hoof-on events with satisfactory accuracy and precision. A pelvis mounted IMU has also been used to detect hoof-on at trot[193]. However, this method used thresholds of velocity and therefore required that the recorded accelerations be integrated to obtain velocities, a process that can be computationally difficult to implement and is prone to significant error, as mentioned previously. Furthermore, previous authors have suggested that the indirect and gait-dependent nature of the linkage between the hoof and trunk will lead to inaccuracies when the latter body segment is used to detect gait events, and that events detected from the distal limb should be used when possible

The methods of Olsen et al.[192] were further developed and validated to detect gait events from distal limb mounted IMUs at trot[76,194]. The method uses the fusion of IMU data to obtain the limb angles to inform the detection of specific peaks in the resultant acceleration which coincide with the instants of hoof-on and -off. Additional methods to detect gait events from IMUs attached to the cannons[195] and hooves[196,197] have also been validated by comparison to events detected using OMC and force plates, respectively.

Despite the number of published methods for gait event detection, the conditions under which they were validated have so far been somewhat limited. For instance, the methods mentioned have only been validated for use on hard surfaces, despite one of the major advantages of IMUs being that they can be used to collect data on any surface. Furthermore, methods tended to only be tested on horses of one breed, either Warmbloods[194,196,197] or trotting horses[195], only Olsen et al.[192] used a variety of breeds. As different breeds of horse can exhibit breed-specific gait kinematics, this could be a significant oversight in the available literature. Finally, only one of the mentioned papers[193] assessed the developed method for data collected on a circle as well as in straight lines.

Although a single axis gyroscope attached to the pastern of the forelimb has often been used in the literature to differentiate between the left- and right-forelimb stance phase[67,72,198–200], the method by which gait events were detected from these data streams are not publicly available. Thus, there are no published methods of gait event detection from pastern-mounted IMUs available in the public domain.

***Summary**: IMUs attached to the distal limbs have been frequently reported to enable accurate and precise detection of the gait events but validation of methods has been limited in terms of surface conditions and cohort characteristics. There are also no published methods for gait event detection using pastern-mounted IMUs.*

2.4 Quantification of the Effect of Lameness on Horse Gait

In the literature, many objective methods of data collection and processing have been proposed and validated to characterise different aspects of equine gait. Many alterations of gait, associated with the presence of lameness, have been measured and significant efforts made to establish which features of gait can be reliably used as a means of detecting and quantifying lameness. These studies are discussed in the following sections and the suitability of the findings as a parameter for detecting lameness, considered.

2.4.1 Effect of lameness on ground reaction forces

In horses measured on an instrumented treadmill at trot, both fore[201] and hindlimb[27] lameness was found to: cause a total reduction in vertical impulse per stride; decrease impulse during the stance of the lame diagonal; shift the impulse to the hindlimb of the affected diagonal pair in forelimb lameness and to the forelimb of the affected pair in hindlimb lameness; and reduce the rate of loading and peak vertical force by prolonging the stance duration.

It is well understood that the mechanisms of lameness aim to relieve loading from a painful limb or limbs onto other, compensating limbs[39]. During healthy walk, the force profile of the vertical GRFs features two peaks[202] and during trot it features one[36,203]. In the presence of lameness, these peaks are reduced, for walk the difference is most notable for the second peak[36,201] (see Fig 2.4). Concurrently, peaks in vertical GRF of the other limbs are increased; in unilateral forelimb lameness, this compensatory effect is particularly evident in the diagonal hindlimb and contralateral, healthy forelimb[36,124]. Some authors have found that the degree of load redistribution with lameness may differ significantly between horses of different breeds, suggesting that the coping mechanisms are breed dependent[204]. Due to its inherently symmetric nature and the higher GRFs seen during the faster pace of trot, it has traditionally been the gait of choice for lameness evaluation, for both visual and quantitative methods. During trot, high vertical impulses produce the suspension phase, in which all four hooves are off the ground, which is indicative of a healthy trot. Impairment of the suspension phase, with a perceived reduction in trot quality, is often the first clinical sign of lameness as the horse seeks to reduce loading of the painful limb and hence cannot achieve the same suspension following stance phase of the affected diagonal limb pair[39]. Reduction in GRFs of the lame forelimb and ipsilateral hind were seen, alongside an increase in those of the contralateral fore and diagonal hindlimb when forelimb lameness was induced in ten sound Warmbloods (Fig 2.4[36]).

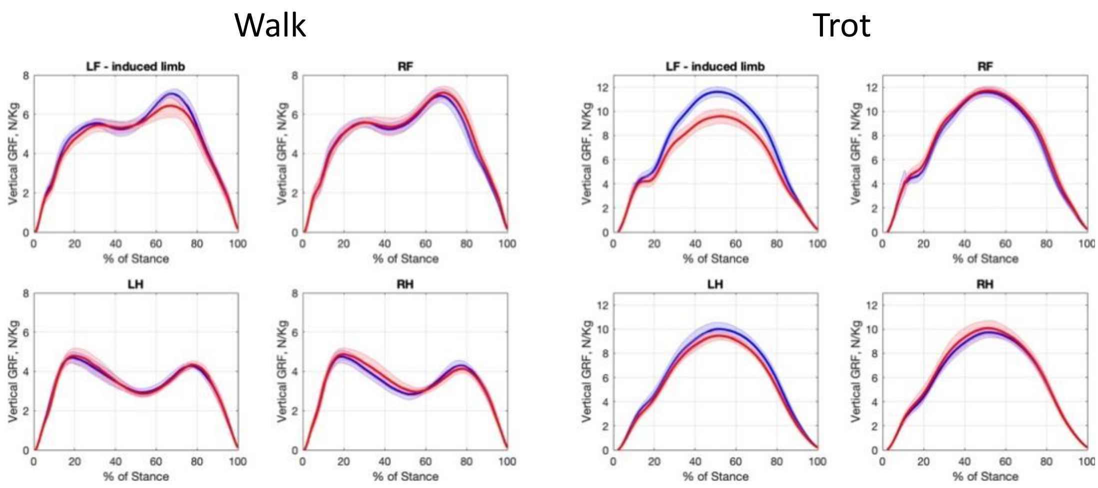


Figure 2.4 Vertical GRFs experienced by limbs during stance phase at walk and trot. GRFs of the left fore (LF), right fore (RF), left hind (LH) and right hind (RH) before (blue) and after (red) lameness induction in LF, are presented during walking (left) and trotting (right). Adapted from Bragança et al.[36].

The horse is able to alter the vertical GRFs, in response to lameness, by adjusting their posture and gait kinematics. As the vertical GRFs cannot be visualised and are difficult to measure, these adjustments of posture and gait form the clinical indications by which lameness is detected. These clinical signs typically include asymmetries in the vertical excursions of the upper body locations, including the head, withers and pelvis.

2.4.2 Effect of lameness on temporal stride parameters

Many attempts have been made to establish relationships between inter- and intralimb contact timings and lameness state[42,51,201]. However, studies have not revealed any consistent alterations or induction of asymmetries in these parameters with lameness.

When fore and hindlimb lameness, in turn, were induced in six sound Warmblood horses, and they were allowed to trot overground at a self-selected speed, the results of video footage revealed several alterations of gait[40]. Horses tended to trot more slowly with fore and hindlimb lameness, (10% and 13%, respectively). The stride duration remained unchanged but stride length became shorter, (9% in forelimb and 10% in hindlimb lameness). Lameness did not induce asymmetry in the stance durations, in agreement with other studies at trot[51,201] and walk[205]. Authors discovered several changes in hoof motion pattern with fore or hindlimb lameness which they explained as being mechanisms of load redistribution away from the lame limb[40]. They cited that the observed changes were better suited for differentiating between fore and hindlimb lameness than they were for differentiating between sound and lame conditions, particularly with the degree of natural asymmetry observed for individual horses even in a sound sate.

When horses are forced to maintain a constant speed after lameness induction, the alterations in temporal gait parameters are different. In contrast to trotting overground, stride duration was found to reduce by 3.1% in forelimb and 3.7% in hindlimb lameness when lameness was induced in eleven Warmblood horses trotting on a treadmill[51]. This result was confirmed in another study when induced forelimb lameness caused a reduction in the stride duration of walk (2%) and trot (3.4%) on a treadmill[36]. Induction of forelimb lameness caused an increase in the relative stance duration in all limbs (5.3% in the forelimbs, 1.5% and 3.2% in the hindlimbs); whereas, with hindlimb lameness, only the relative stance duration of the sound hindlimb was found to be affected, increasing by 2.7%[51]. As in overground trotting, stance duration symmetry was maintained. The suspension phase following push off from the lame diagonal was reduced by 61% during forelimb lameness and suspension following sound diagonal stance remained unchanged. No changes in suspension phase were reported with hindlimb lameness[51]. At walk, lameness was found to have almost no effect on the temporal gait pattern, having no effect on the stride duration and only minor effects on any inter- or intralimb timings. Hence, this paper concluded that changes in temporal stride patterns with lameness were more evident at trot than walk and that the compensatory effects of forelimb lameness were more pronounced than those of hindlimb lameness. Authors also cited that the maintenance of symmetry in most temporal stride patterns, with increasing lameness, limits their use as indicators of lameness, particularly in cases of mild lameness. Hence, authors concluded that changes in temporal stride patterns alone should not be used as a means of detecting lameness[51].

In twenty-one cases of spontaneous forelimb lameness, horses were trotted on a treadmill and the stride lengths were measured before and after lameness was reversed using analgesic blocks[206]. Variability in stride duration was found to be lower when the horse was lame compared to after lameness was relieved which authors suggested was because, when lame, the horse adopts an optimum compensatory mechanism and deviations from this increase pain. However, when analysed on the group level, there was significant overlap in the range of stride length variabilities seen with lameness (0.77% to 3.12%) and after blocks were administered (0.87% to 3.25%). Hence, the variability of stride length cannot be used as a parameter to distinguish between sound and lame states.

Only a handful of publications exist which investigated the effect of forelimb lameness on breakover duration and none which investigated the effects of hindlimb lameness. In three separate case studies, the breakover duration of the affected forelimb was significantly longer than that of the contralateral, sound limb in a non-articular shoulder fracture[43], chronic sesamoiditis of the fetlock joint[42] and fracture of the third carpal bone[207]. Despite these observations, there has been very little subsequent research into the effect of lameness on breakover duration. Small differences were reported between the breakover duration of the forelimb before and after lameness induction in six sound Quarter horses at walk[205] and trot[208]. The magnitude of differences were not correlated with the degree of lameness and no differences were seen between the breakover durations of the lame and contralateral, sound limb, in contrast to the previous findings[42,43,207].

***Summary**: previous studies state that temporal stride parameters, including symmetry of stance durations, cannot be used as a means of detecting lameness. The relationship between lameness and breakover duration remains poorly understood due to a lack of research on the subject.*

2.4.3 Effect of lameness on limb movement

It has been reported that inducing forelimb lameness in six sound Quarter horses caused significant changes in the hoof orientations[205,208,209], with increases in external rotation and abduction and decreases in sagittal plane rotation of the hoof during breakover of the lame limb[209]. At walk, the lame forelimb had more restricted sagittal-plane movements compared to the contralateral forelimb[205] . When forelimb lameness was induced in ten sound Warmbloods, both protraction and retraction angles of all limbs were found to decrease at walk while increased protraction angles and decreased retraction angles were reported at trot[36]. Despite these reported differences with lameness, measurements of limb angles may not be a reliable means of detecting lameness as, in all cases, the greatest change in limb angle due to lameness was only 1.3°. Furthermore, results suggested that comparison of the joint angles of the left and right contralateral limbs was no sufficient to identify lameness[110]. Hence, limb angles alone should not be relied upon as a means of detecting lameness.

The left-right symmetry of the vertical joint displacements and joint angles were investigated in a highly varied cohort of thirteen sound horses, twelve with unilateral forelimb lameness and twelve with unilateral hindlimb lameness[110]. Symmetry of both vertical joint displacements and joints angles were impaired with fore and hindlimb lameness, with the former being more commonly impaired. Forelimb lameness was found to most commonly affect the movement symmetry of the forelimbs and hindlimb lameness that of the hindlimbs. Furthermore, compensatory effects of hindlimb lameness on the forelimb movements were more often present than compensatory effects of forelimb lameness on the hindlimbs. This agrees with other literature which cites hindlimb lameness as more often causing a compensatory, apparent forelimb lameness than vice versa[49,67].

__Summary__: lameness induces changes in the limb angles but the magnitudes of these are too small for them to be reliably used as a means of detecting lameness. Changes in vertical limb movement suggest that forelimb lameness affects the fore end of the horse most while hindlimb lameness affects the hind; hindlimb lameness induces a compensatory forelimb lameness more commonly than forelimb lameness induces a compensatory hindlimb lameness.

2.4.4 Effect of lameness on upper body kinematics

An understanding of its effects on the temporal gait parameters and limb kinematics is vital for a thorough understanding of the mechanisms of lameness. However, the most consistently reported cardinal signs of lameness, and the ones on which both subjective and objective methods tend to be predicated on, are its effects on the upper body movement symmetry[25,61,71,210]. Current state-of-the-art systems measure the vertical displacements (using either OMC[107,115] methods or IMU recordings and double integration[76,77,80,177,211,212]) of the poll, withers and/or croup during the two similar oscillations of the stride cycle of the inherently symmetric gaits of walk and trot[25,36]. By comparing the maximum and minimum displacements recorded during successive cycles, quantifications of gait symmetry can be calculated.

Explained simply, the vertical displacements of the upper body are reduced during the stance phase of a lame limb and may be increased during that of the contralateral, healthy limb[73]. This can be understood by the mechanism described in a previous section (1.5.3 Effect of lameness on head and trunk movement). Recall, the linear relationship between the fetlock joint angle and forces experienced by the limb[63] indicate that there is a reduced fetlock drop during the stance phase of a lame limb, where the GRFs are reduced. This means that the upper body, attached to the fetlock joint through the linkage of the limbs, does not reach as low a minimum position during the stance of the lame limb (Fig 2.5, $minima_2$) compared to that of the contralateral limb (Fig 2.5, $minima_1$). Thus, the reduced vertical motion of the trunk is related reduced peak force in a lame limb. Furthermore, reduced propulsion from a lame diagonal may result in a lower maximum position being reached after the stance of the lame limb (Fig 2.5, $maxima_2$) compared to that after the sound (Fig 2.5, $maxima_1$). Fig 2.5 illustrates the temporospatial parameters which current state-of-the-art systems measure, using these to calculate symmetry indices based on comparison of values associated with the stance of the sound diagonal (Fig 2.5, subscript 1) with those of the lame (Fig 2.5, subscript 2).

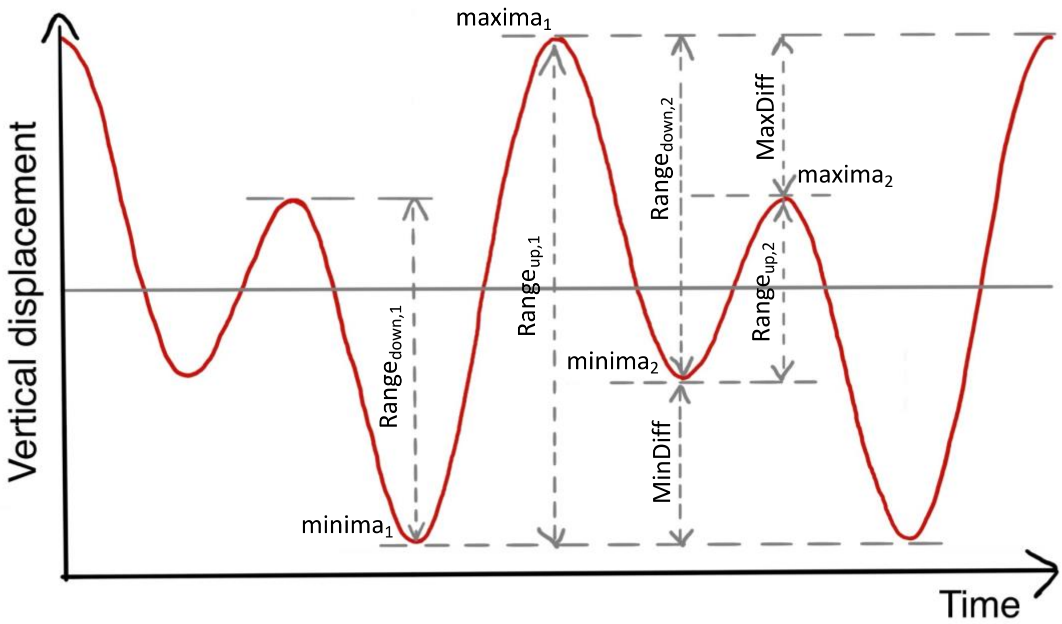


Illustration of the vertical upper body motion of a lame horse showing the values of interest calculated by many state-of-the-art methods and systems. Values associated with the stance of the sound diagonal are labelled with the subscript 1, and those with the lame diagonal are labelled 2. Based on the figures of Bosch et al.[76]

Symmetry indices calculated from the vertical poll motion[74], and absolute maxima and minima of the croup[80] have been found to be correlated to the GRFs experienced by the fore and hindlimbs, respectively. Hence, not only can the motion of the upper body be used as an indication of lameness, but the asymmetries are directly related to the asymmetries of GRF which are the fundamental change made to accommodate pain.

Thus, methods of vertical upper body movement quantification mimic the subjective observations made by clinicians when assessing the degree of head nod and hip hike. Although some asymmetries have been measured at walk, these are not as pronounced as those seen at trot[36] and thus, while many methods are theoretically applicable to walk and trot, application often focusses on trot.

In subjective lameness assessments, evaluation under different conditions (such as while circling on the lunge and on different surfaces) forms a key element of workups and the methods described above are increasingly being used to assess horses under such conditions[213]. It has been identified that circling has the effect of inducing asymmetric gait which may appear as lameness even in sound horses displaying symmetric gait in straight lines[114,200], which is in keeping with the observation that the inside and outside limbs experience different peak vertical forces and impacts during circling[149]. Therefore, additional efforts have since investigated the effect of circling on the movement symmetry of lame horses[98]. These have found that lame horses show an increased degree of poll asymmetry when exercised on the lunge, compared to in straight lines, and that this factor is more pronounced when the lame limb is on the inside of the circle. Sound horses showed an equal degree of poll movement symmetry when lunged in both directions. Thus, lunging may be used to exacerbate lameness, facilitating the detection of mild cases, as well as helping to discriminate between the left- and right-limb lameness.

Similarly, for sound horses two different surfaces- hard (concrete) and soft (sand and rubber)- were found to have no effect on the poll motion symmetry whereas forelimb lame horses showed an even higher degree of asymmetry when lunged on a hard surface, compared to soft. These methods have also been applied to data collected before and after delivery of analgesic nerve blocks to the foot[101]. This study found the system was able to detect changes in vertical head and pelvic movement as a result of a positive response to nerve-blocking. While some have suggested that methods of vertical displacement quantification may not be reliable for detecting bilateral lameness cases where the severity is equal in both limbs of the pair[74,111] (as these horses may present with symmetric gait), the study mentioned above suggests that they would be ablet to identify such cases when used alongside diagnostic analgesia.

Thus, by using methods of vertical displacement quantification to assess horses under a range of different conditions (including circles, different surfaces, with and without diagnostic analgesia), the usefulness of such systems may be extended to more complicated cases of lameness such as bilateral or mild lameness, which may not present at all when the horse is only assessed in a straight-line. Furthermore, it has been suggested that the use of different test conditions may be useful for further characterisation of lameness, helping to identify whether pain is associated with the landing or propulsion phase of the stride cycle and, hence, helping to identify the specific cause of lameness from what movement adaptations are apparent.

Owing to the close relationship between linear displacement, velocity and acceleration, the sinusoidal curves of the higher derivatives of vertical trunk and head movement are similar to those of the linear displacement. With each derivation, the sinusoidal curve is shifted by 12.5% of a stride cycle to the left, along the x-axis, in a plot of kinematic variable against time (Fig 2.6)[25]. Hence, the vertical displacements, velocities or accelerations can be used in similar ways to evaluate the symmetry of upper body motion in horses. Indeed, methods based on accelerations could be more robust to changes in vertical motion due to extraneous events, such as the horse lifting their head in a spook, than those based on displacements as accelerations are less sensitive to changes in absolute head height and maximal values[23]. Furthermore, the interpretation of changes in vertical acceleration are quite intuitive as they are directly representative of the vertical forces acting on the limbs, due to Newton's Second Law (Eq 2.1) describing the relationship between force (F), mass (m) and acceleration (a). Thus, reduced vertical accelerations of the midline during the stance of phase of a lame limb can be easily understood to represent the reduced loading experienced by the limb.

$$F = ma \qquad (2.1)$$

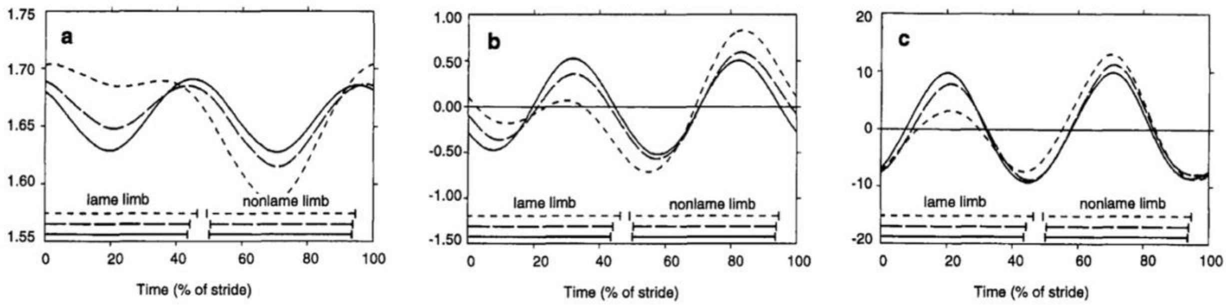


Figure 2.6 illustration of the mean vertical poll displacement (a), velocity (b) and acceleration (c) in sound (——), grade 1 (— —) and grade 2 (- - -) lameness conditions. With each derivation, the sinusoidal curve is hastened by 12.5%. Adapted from Buchner et al.[25].

Methods based directly on the vertical displacements of upper body locations, have been applied to detect and quantify both fore[36] and hindlimb[76] lameness cases. These studies found that significant differences between the minimum and maximum positions reached by the upper body locations during the stance phases of the left- and right-diagonal limb pairs at trot could be used as a reliable indication of lameness. Analysing data recorded from locations at the fore end of the horse (for example the poll) has been cited as more informative of forelimb lameness, while data from the hind end (for example the pelvis) is more suited to analysis of hindlimb lameness[77]. Differences in vertical poll displacement during forelimb lameness have been found to be substantially larger than those of the pelvis during hindlimb lameness.

Owing to the complication of false, compensatory lameness, these methods have also been applied to the vertical displacement of the withers. When lameness was induced in each limb of ten sound Warmbloods in turn, the minimum position of the poll, withers and pelvis were found to be significantly affected by fore and hindlimb lameness compared to sound baseline readings[71]. It was found that the sign of the difference in minimum wither displacement could be used to differentiate between primary forelimb and primary hindlimb lameness cases which induce a false, compensatory lameness in the contralateral hindlimb and ipsilateral forelimb, respectively.

Methods of movement symmetry analysis such as these have been used extensively, proving useful under a range of different experimental conditions including for locomotion recorded overground[214] and on a treadmill[36]; and in cases of naturally occurring[77] and experimentally induced lameness[36]. These methods have also been used in applications other than lameness detection; for example, to investigate the effect of circling[114,200,215] and soft versus hard surfaces on movement asymmetry in horses deemed sound when trotted on a hard surface in a straight-line[98]. These studies found that circling has the effect of inducing asymmetric movement even in sound horses; hence, it has been proposed that different threshold values to distinguish lame from sound cases need to be established for the specific application of circling[114].

It has been suggested that use of the absolute vertical displacement of body landmarks may have its shortcomings, especially when used to analyse vertical poll movement over which the horse has most autonomy. Data collected using a marker or IMU attached to the poll is most severely affected by extraneous events, such as the horse lifting their head unusually high during a spook. Several authors have developed methods of signal processing which aim to remove extraneous events from vertical displacement signals. These are based on methods of signal decomposition, which assume the vertical motion of the horse's head during the cyclic gait of trot, can be decomposed into three components- one biphasic and one phasic, attributable to the normal gait cycle and once per stride cycle events arising due to unilateral lameness respectively (Fig 2.7) and a third, low frequency component due to extraneous events[61]. By decomposing the vertical displacement signal thus, these methods seek to remove the extraneous events and quantify the degree of gait symmetry by investigating the relative contribution of the first and second components, only. These methods have been applied to data collected from two orthogonal accelerometers attached to the poll of horses to detect forelimb lameness[61], and to the croup to detect hindlimb lameness[216].

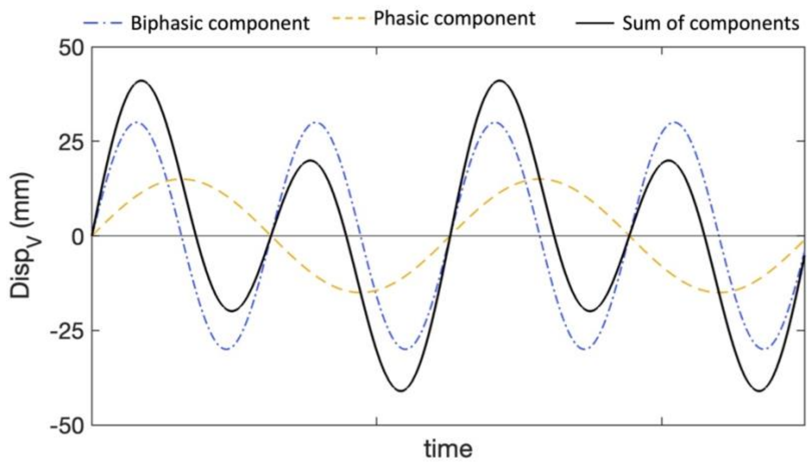


Figure 2.7 illustration of signal decomposition of the vertical upper body motion during unilateral lameness. The biphasic component attributable to healthy gait (blue dash-dot line), phasic component associated with unilateral lameness (gold dashed line) and sum of the two, representing the vertical motion of the unilaterally lame horse (black line) are given. The example values of vertical displacement (Disp$_V$) have been chosen after scrutiny of the literature [29,61,71,73,76,217].

Closely linked to these methods of signal decomposition, application of Fourier methods has also been proposed. By obtaining the Fourier transform of the vertical motion signals, researchers analysed the vertical movement of the horse in the frequency domain[210,218]. For a horse whose movement is perfectly symmetrical, the frequency content of the vertical upper body movements at trot will be concentrated around a single harmonic which is equal to double the stride frequency (Fig 2.8, bottom left). When the movement becomes asymmetric, a second harmonic will be seen, equal to the stride frequency (Fig 2.8, bottom right). A symmetry score based on the relative contribution of these two harmonics has been found useful for determining the source and severity of twenty-nine cases of spontaneous forelimb lameness[218]. Since, the method has also been applied to acceleration signals collected from a poll mounted sensor to determine the effect of tranquilizer on lame horses[219]. In agreement with other literature[220], the study found that sedation did not affect the local stability of gait.

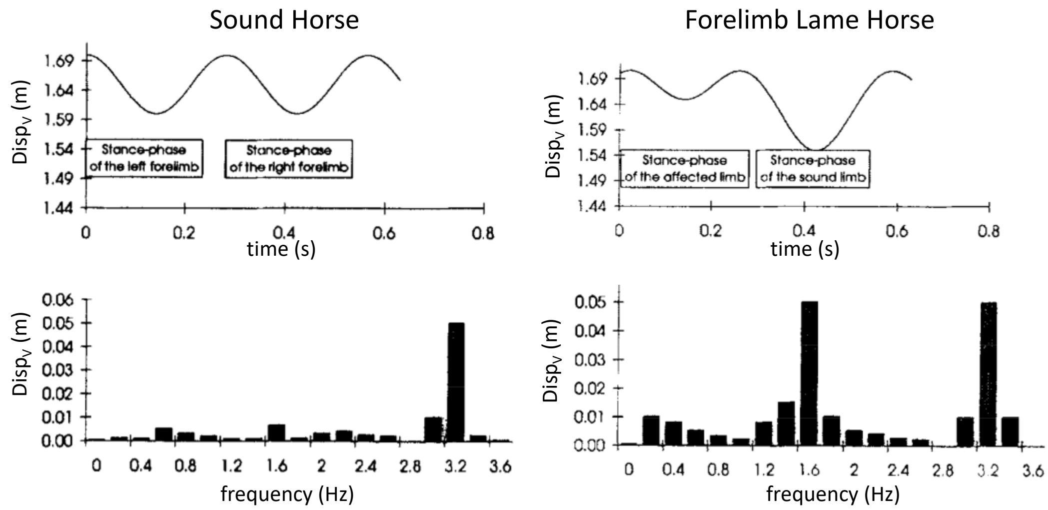


Figure 2.8 illustration of frequency domain methods. Examples of vertical poll displacements (Disp$_V$) in the time (top panels) and frequency (bottom panels) domains are given for a sound (left panels) and forelimb lame (right panels) horse. Adapted from Peham and Licka[210].

When OMC technology is not available or is not convenient, IMUs are often used instead. Methods to derive linear displacements from IMU collected data are available[177] and have been widely adopted throughout the literature for the application of lameness detection based on vertical displacements, proving to yield reliable and repeatable results which are clinically relevant[76]. However, the potential for introducing errors during the integration process means that methods based on analysis of the linear accelerations, directly, are also worth consideration. As mentioned previously, these methods might also be more closely linked to the changes in limb loading, which are characteristic of lameness, due to the relationship between acceleration and force[221].

One method of signal processing which has previously been applied to the accelerations directly is autocorrelation which calculates the correlation of a signal with itself delayed in time and has been applied extensively in human research to analyse gait[222,223]. In the function of autocorrelation coefficient, the first peak (Ad1) represents the correlation of the signal with itself delayed by a half stride cycle and is thus a measure of gait symmetry. The second peak (Ad2) in the autocorrelation function quantifies how well the signal correlates to itself delayed by a whole stride cycle, thus quantifying gait regularity. In a pilot study to develop autocorrelation methods to differentiate between sound and lame gait[224], the Ad1 value calculated from dorsoventral accelerations of the sternum at trot were found to be reduced from 0.67 to 0.49 following induction of moderate unilateral forelimb lameness in a single horse and Ad2 was reduced from 0.65 to 0.48, accordingly. These results indicate that Ad1 can be used to measure increased degrees of asymmetry with unilateral forelimb lameness and suggest that gait regularity also decreases with lameness. There appear, however, to be some inconsistencies when autocorrelation is used elsewhere in the literature. In a later study, authors used a cohort of young, sound horses at trot to establish threshold Ad1 and Ad2 values taken from the autocorrelation of the dorsoventral and mediolateral accelerations of the sternum and sacrum to differentiate between sound and lame gait[225]. They found Ad1 >0.98 indicated a sound gait, 0.96-0.98 ‘suspicious’ gait symmetry and <0.96 the gait was ‘symmetrically abnormal’. Using these thresholds, the horse examined in the previous study would be classed as having highly abnormal, asymmetric gait. In both studies, the gait data was recorded on a treadmill. This observation highlights the need for careful interpretation of the results of autocorrelation methods. It may be that the single sound horse used by Barrey et al.[224] was an example of an individual whose natural, healthy gait showed more variation, or a higher degree of asymmetry, than those expected in a cohort of sound horses. This is also another argument in support of using horse-specific thresholds, such as using methods of left-right symmetry quantification, to determine the degree of asymmetry, rather than using blanket threshold values across entire populations of horses. A warning against adoption of such thresholds has previously been raised and discussed in detail[111,226,227]. Methods of autocorrelation have also been used to assess the walk and trot of six sound horses and twenty-six lame horses presented to a veterinary clinic for examination[228]. The method proved useful for quantifying the degree of lameness and identifying the lame limb when the results of quantitative methods were compared to the findings of an experienced clinician. It was also highlighted that the method might prove most valuable for detection of mild lameness at walk. This is an important observation as many of the methods of lameness quantification are optimised for data collected at trot, even though it has been highlighted that walk may be more sensitive to subtle lameness[36].

Despite early promise, methods of autocorrelation have not since been developed as a means of differentiating between sound and lame horses in larger cohorts. Instead, it has been used to establish whether stride symmetry and regularity can be used as indicators of performance in dressage[229,230] and racehorses[231,232]. More recently, methods of autocorrelation have been used to establish the maximum safe load for Japanese native ponies to carry[233,234].

Other authors developed methods of lameness quantification which were applied directly to dorsoventral accelerations recorded by an accelerometer attached to the withers (Fig 2.9)[221]. Again, these were based on the theory that the biphasic vertical motion of the horse’s upper body are approximately equal for both halves of the stride cycle during trot in a sound horse. Fourier expansion of the dorsoventral acceleration, similar to the signal decomposition methods discussed previously (Fig 2.9, left panel), was used first to establish whether the horse’s gait was asymmetric by comparing the relative contribution of the even harmonics, describing the symmetric movement, and odd harmonics, describing the asymmetric. Area under the two positive halves of the dorsoventral acceleration curve (Fig 2.9, middle panel), one being correlated with the left diagonal stance phase and one with the right, were compared; a smaller area under the curve was expected to be discovered during the stance of a lame diagonal limb pair, compared to that of the sound. Thus, the method could be used to determine in which diagonal pair the lame limb was. Finally, the phase difference of the left and right diagonal stance phases within the stride were investigated by analysis of the dorsoventral acceleration curve (Fig 2.9, right panel). It was surmised that the suspension phase after the stance of a lame diagonal limb pair would be shorter than after that of a sound diagonal limb pair and, thus, contralateral advanced placement of the lame to sound limb would be decreased. Assuming that this effect would be more pronounced for forelimb lameness than hind, the methods hence sought to determine not only whether the horse was lame and in which diagonal limb pair the affected limb was in, but also whether it was the fore or hindlimb of the pair that was lame. Initially, these indices were investigated in a cohort of twelve sound trotting horses. Methods were reliably able to describe a high degree of symmetry in the movement of the sound horses at trot and the repeat measures proved the indices were highly repeatable. Later, the first two indices were investigated before and after transient lameness induction in six sound horses trotting at a self-selected speed on asphalt[235]. Results showed a strong relationship between the degree of lameness identified using the symmetry scores and that assigned when an experienced clinician used the visual AAEP scoring methods. Authors cited that, while the methods were effective for classifying mild to moderate forelimb lameness, when Grade 4 lameness was induced in one horse, the horse was unable to maintain a regular trot, a prerequisite for the application of Fourier methods, and hence the methods were unusable. This is an important observation as it could limit the usefulness of the methods for clinical application where steady trot may not always be possible, either due to severe lameness, as in this example, or some other external factor. The derivation and interpretation of the developed indices were described in greater detail in a later publication[236] where there proved to be a high correlation between the actual lameness state of horses and the lameness state identified by the symmetry indices. Thus, analysis of the dorsoventral trunk accelerations, directly, may be useful for detecting lameness as well as identifying the lame limb, in cases of unilateral lameness where the horse is able to be measured at a regular trot.

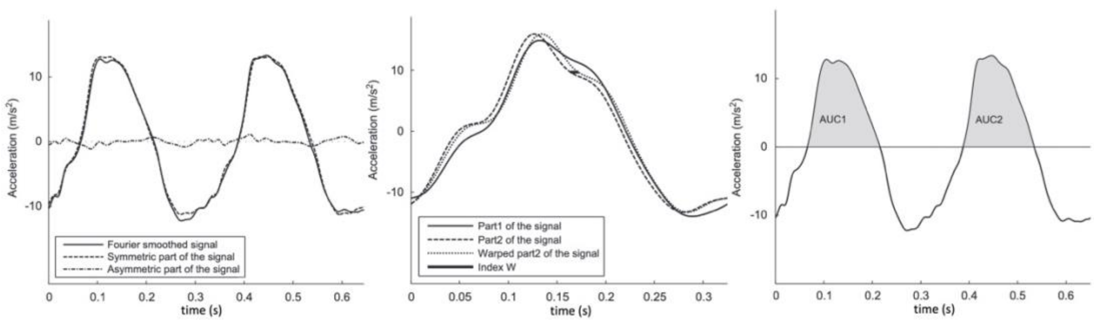


Figure 2.9 illustration of the methods of Fourier smoothing, signal warping and area under the curve developed by Thomsen et al. Adapted from Thomsen et al.[221]

From the discussion of previous efforts to develop a tool to detect and quantify lameness, it is apparent that although the effect of lameness on walk has been explored in a few publications, its effect on trot is far more widely documented and the tools developed thus far have generally been optimised for analysing trot. Furthermore, although there has been extensive research into the effect of lameness on upper body symmetry and on temporal stride parameters under a variety of different test conditions, there remains a paucity of publications which relate the behaviour of the temporal stride parameters to the motion of the upper body. In one study which sort to address both these omissions in the literature, unilateral forelimb lameness was induced using a sole-pressure model in a cohort of ten sound Warmbloods[36]; the effects of lameness on the lower and upper body at walk and trot on an instrumented treadmill were explored using OMC. At both walk and trot, forelimb lameness was discovered to induce significant changes in the vertical GRFs (Fig 2.10) and impulses, in agreement with previous literature[41,65,66,123]. Several changes in the limb kinematics and temporal stride parameters were observed, at walk and trot. The changes in head and wither movement symmetry recorded at trot agreed with other literature which explored the effect of induced fore and hindlimb lameness[71]. The minimum displacement of both the head and withers were found to be significantly reduced after the induction of lameness, with the effect being far more pronounced in the head than the withers. The maximum displacement of the head was also significantly reduced during the stance phase of the lame limb. At walk, similar alterations in the upper body symmetry were seen but these were not as pronounced as for trot (Fig 2.10). Furthermore, while the total range of dorsoventral head motion was significantly increased by 50% after the induction of lameness, at walk the increase was much smaller (6.7%) and not statistically significant. As in trot, authors cited that head movement and forelimb vertical force symmetry seemed to be the most useful parameters for the detection of forelimb lameness at walk and highlighted that, while differences due to lameness seem to be less pronounced at walk than trot, agreeing with previous studies[25,26], several differences are seen at walk which are not detected at trot. Therefore, walk should not be neglected when exploring the effect of lameness on equine locomotion.

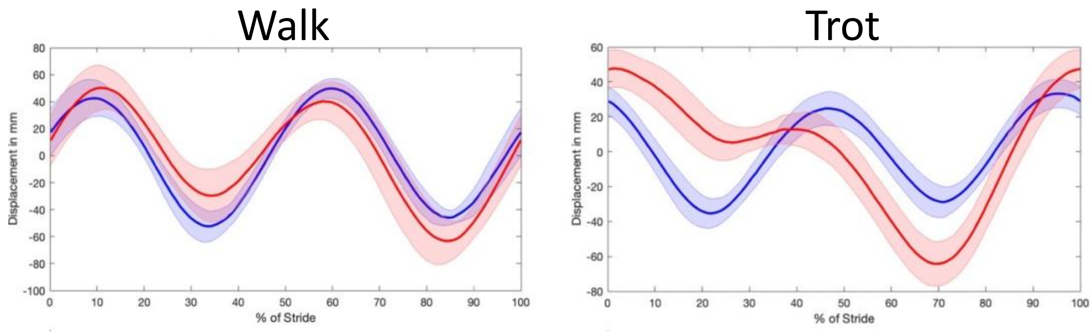


Figure 2.10 vertical poll displacement before (blue) and after (red) induction of left forelimb lameness at walk (left) and trot (right). Adapted from Bragança et al.[36].

***Summary**: although many methods have been developed for the quantification of gait symmetry at trot, there is a lack of methods which are optimised for walk. There is also a lack of literature which links the temporal gait characteristics to the symmetry of the upper body.*

2.5 Adoption of Quantitative Methods in Clinical Practice

Despite the significant advances which have been made in the area of equine lameness detection and quantification, adoption of technologies has been slow in the applied field[237] and the methods are still not routinely adopted during clinical practice by the majority of practicing equine vets[127,161]. This is perhaps surprising as lameness and other dysfunctions of the locomotor system are reported to be the biggest problem faced by owners, riders and trainers across all levels and equestrian disciplines[170,238].

Results of a recent survey study of seventy-two equine clinicians[161] highlighted a majority (60%) of those questioned sometimes doubted their subjective opinion during subjective lameness examinations, while 30% often doubted it and 7.5% always doubted it. These figures support efforts towards developing a comprehensive quantitative system to reliably detect lameness, identifying the most affected limb(s) and grading the lameness, as a tool to support the subjective observations of an experienced clinician and inform the clinical decision making. The results of the same study, shown in Fig 2.11, indicate that the perceived usefulness of quantitative gait analysis methods was higher among users (82.5% positive or very positive) than nonusers (62.6% positive or very positive), and the results of both groups suggest that veterinary clinicians are not, on whole, averse to the introduction of such tools. The findings of this survey, albeit limited in sample size, should further encourage the development of tools for lameness detection and quantification.

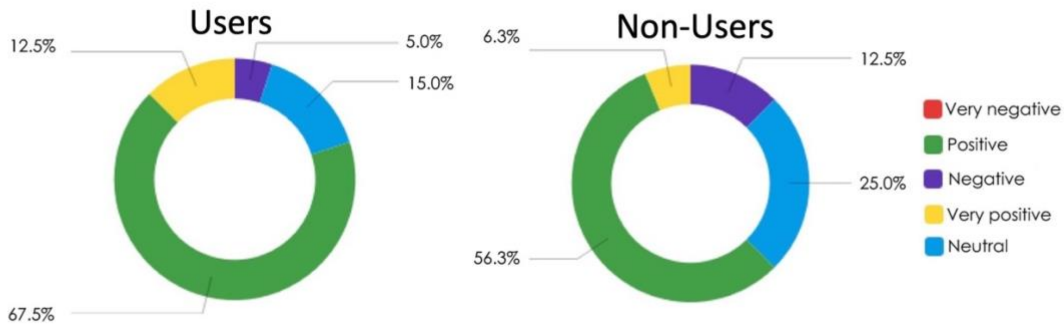


Figure 2.115 illustration of the perceived usefulness of quantitative equine gait analysis methods by users (n=40, left) and non-users (n=32, right). Adapted from Hardeman et al.[161].

When these systems are introduced into clinical environments, debate ensues around the distinction between 'lameness' and 'asymmetry'. Lameness is a clinical sign of an underlying, pathological cause and is often, especially in cases of unilateral lameness, accompanied by an increased degree of asymmetry in gait[111]. Contrastingly, asymmetry, the feature of gait which is most often the basis of lameness detection systems, refers to any deviations from a perfectly symmetric gait, without indication of the causation, which could arise for many reasons including natural sidedness[30,239–241], biological inter- or intraindividual variation[200,242] or lameness due to pain or neurological conditions[20]. It has been suggested by some that 'lameness' and 'asymmetry' are not equivalent and must not be used interchangeably[111,161,243], as additional research into whether all visible and measurable asymmetries are the result of orthopaedic pain is necessary. It has been suggested that the measured variables, which are the outcomes of objective gait analysis, must be supported by scientific evidence and a thorough understanding of the biomechanical principles of equine gait[127]. Thus, interpretation of such outputs should be interpreted by a knowledgeable person such as a veterinary clinician, who can also take into account external factors such as the intended use of the individual horse.

Hence, it is important to consider objective tools and methods as a means of enabling further understanding of the mechanics of lameness and a way of informing the clinical decision making, rather than a means of making clinical decisions[226,227]. Previous authors state that it is desirable for the results of body mounted inertial sensor systems to be used in conjunction with the expertise of an experienced clinician using visual techniques[244]. Thus, when advancing tools for lameness detection, researchers should aim to develop systems which are complimentary to the existing methods used by veterinary clinicians.

One impediment to the more widespread adoption of objective systems in daily clinical practice might be due to the frequency of false positives and negatives incurred by such systems. In a retrospective study of 1224 horses assessed using body mounted IMUs, the initial lameness state, as identified by the IMU system, was compared to the final diagnosis after full clinical investigations[245]. Of 103 horses which were detected as sound by the IMU system, only 55% transpired to be sound after full investigations. Of 109 horses deemed forelimb and 158 hindlimb lame by the system, only 59% and 65% of horses, respectively, were revealed to have been correctly classified, following full investigations. This study found that the system was most unreliable for detecting lameness involving multiple limbs. The system initially classified 693 horses as being multilimb lame; of these, only 13% transpired to be suffering true multilimb lameness. Thus, despite the significant advancements in technology and processing methodologies, there is still scope for substantial improvements to be made regarding the reliability of diagnostic systems.

The low reliability of these systems for detecting multilimb lameness may be due to the means by which lameness is detected. As discussed previously, these systems detect the degree of asymmetry in the gait to assist in lameness detection. Thus, the detection is predicated on the lameness being either unilateral or one limb of the contralateral limb pair being more severely affected than the other, to allow detection of asymmetry. Hence, the systems may not be reliable for the detection of truly bilateral lameness[246]. As discussed previously, it has been proposed that the use of diagnostic analgesia, used in conjunction with quantitative systems, may be the solution to identifying bilateral lameness[101]. This is especially relevant when the horse is used as its own control and a pre-lameness state can be created with nerve blocks, to collect the control data. Thus, the developed systems could work comprehensively in compliment with current clinical practices where nerve blocking is common.

***Summary**: despite advances in the field of quantitative equine gait analysis, adoption of the methods into clinical practice is still limited. There is scope for improvements to be made in the reliability of such systems for classifying lameness state.*

2.6 Aims and Objectives

Briefly summarising the main points, lameness continues to be the most prevalent problem facing equines in all walks of life. While subjective methods remain the most commonly adopted means of detecting lameness, the widely reported limitations of such visual assessments have led to the development of quantitative methods. These make use of a wide variety of gait measuring devices but IMUs are currently the most promising for data collection in the field. While several methods of IMU based gait event detection have been proposed and validated in the literature, these have been somewhat limited in terms of the horses and surfaces they were tested on. The effect of lameness on many aspects of gait have now been investigated, including the effect on various temporal gait parameters; however, the effect of lameness on breakover duration has been largely overlooked. Many different methods of lameness detection have been proposed, validated and adopted in the literature and these have mostly been based on changes in the vertical movement of the upper body, with lameness. However, these methods have generally been optimised and used for gait analysis at trot and there is a total lack of methods specifically designed for lameness detection at walk.

Considering these points, the overall aim of this research project was:

***Aim**: to develop methods to quantify equine gait suitable for lameness detection and assessment under field conditions and suitable for use in diverse cohorts of horses.*

In order to address this overall aim, the following specific objectives and associated tasks were identified:

Objective 1 To propose and validate methods of gait event detection suitable for use in a variety of field conditions

i. For walk and trot in a straight-line on a hard surface, test signal processing methods from the literature and novel methods, on a highly varied cohort of horses, to determine which are the most accurate and precise for detecting hoof-on and -off from IMUs attached to the distal limbs by validating them against a current state-of-the-art method using hoof-mounted IMUs

ii. Determine where on the distal limb (cannon or pastern) IMUs should be attached to achieve the most accurate and precise event detection

iii. Validate use of the most successful gait event detection methods (identified by tasks i and ii) for detection of events on two additional surfaces- grass and sand

Objective 2 To quantify the effect of lameness on breakover duration

i. Characterise the behaviour of breakover duration in sound and lame horses at walk and trot

ii. Determine the effect of fore and hindlimb lameness on breakover duration, testing the hypothesis that unilateral-dominant lameness affects the contralateral symmetry in the breakover duration of the affected limb pair, inducing a longer breakover duration in the lame limb compared to the contralateral limb

iii. Establish whether patterns in the effect of lameness on breakover duration (established by task ii) can be used as a means of classifying sound and lame horses

Objective 3 To investigate the relationship between breakover duration and the symmetry of the vertical upper body motion in the presence of lameness

i. Characterise the upper body movement symmetry of a cohort of sound and fore and hindlimb lame horses at walk and trot using methods from the literature applied to data collected using IMUs

ii. Establish which gait (walk or trot) and attachment location (poll or croup) is best able to capture features of gait symmetry

iii. Conduct an association analysis by applying methods of linear regression to establish whether there is a cause/effect relationship between the behaviour of breakover duration with lameness, (established in Objective 2) and the upper body movement symmetry

Chapter 3 Gait Events Detection Using Inertial Measurement Units

3.1 Introduction

In both equine sport and medicine, there is increasing demand for quantitative analysis of gait under field conditions[170]. Many techniques are predicated on the reliable detection of the gait events hoof-on and -off, when the hoof first contacts with the ground and is lifted from it, respectively[174,247].

Methods to accurately detect gait events are valuable in various applications including performance analysis and lameness quantification. For instance, an increase in positive diagonal advanced placement (in which the hoof-on of the hindlimb precedes that of the contralateral forelimb) has been found to be an indicator of superior gait quality in advanced dressage horses[248] and approved Warmblood stallions[249]. Furthermore, the timing of gait events can be used to calculate the suspension duration, (when all four hooves are off the ground) which has been found to be significantly reduced by forelimb lameness[43,51,201].

The gold standard of gait event detection remains the force plate[127], which can directly measure ground reaction forces to differentiate between the load-bearing stance phase of a limb and swing phase. However, force plates not only come with extremely high costs but limit the number of strides which can be analysed, requiring a single foot to be placed fully on the plate for reliable analysis. Instrumented treadmills[36] have been used to overcome the latter point but these are often unsuitable for simulating real-world scenarios. Although a very limited number of studies have now used force plates in field conditions[130,131] the obvious complexities of integrating them into surfaces limit wider adoption of such methods. These factors make force plates unsuitable for collecting data under field conditions.

As such, efforts have been made to develop methods which use portable devices. Particularly, wearable inertial measurement units (IMUs) have been heralded as a potential solution to the problem of gait event detection in the field, being relatively inexpensive and highly convenient, (compared to the alternative force plate or optical motion capture systems). Their portability and suitability for outdoor use[250] enable data collection over any range of distance and conditions[161]. They are also comparatively easy to attach to subjects compared to some alternative systems, (such as those which attach pressure measuring devices to the hooves[156,251]) reducing set-up times and being less cumbersome[187] and thus minimising their effect on the horse's movement.

Linear accelerations and angular velocities recorded from IMUs attached to the lateral hoof walls have been successfully used to identify gait events[196,197] on a hard surface. Distinctive peaks in the resultants of acceleration and angular velocity were found to coincide with instances of hoof-on and -off registered simultaneously by a force plate. While features of the stride cycle might be most obvious and distinctive in signals recorded at the level of the hooves[174] securing devices thus is not always practicable- attachment being time consuming and there being a high risk of damage to sensors during data collection. Conversely, most horses very quickly become acclimatised to boots and wraps worn on the cannons or pasterns; hence, this study sought to develop methods of gait event detection which used sensors mounted in these locations. A previous study recorded accelerations from the lateral aspects of the hooves and pasterns of horses during walk, trot and canter[174]. Gait events were manually selected from these profiles and it was found that, while the hoof-on events could be satisfactorily detected from pastern accelerations, hoof-off events were difficult to detect reliably, especially on soft surfaces. Several other studies have used inertial devices attached to the pasterns to identify strides[67,72,200,252], and there is a commercial system which uses these methods (Lameness Locator). However, to the author's best knowledge, there are no published methods for automatic detection of specific gait events from pastern-mounted devices.

Current state-of-the-art methods attach IMUs at the level of the cannon bone[194] or upper body[192] but validation of these have been limited in terms of subject cohorts and surface conditions. Physical characteristics of the individual horse can cause differences in kinematics. For instance, breed-specific conformation[253] can significantly affect gait[254]; age can influence movement, with older horses showing signs of stiffened gait, for example due to osteoarthritis[255]; and whether the horse is shod (wears horseshoes) can have an influence[256]. Furthermore, extensive research has found that surface type has a significant effect on the horse's kinematics[257]. Despite these reported variations, previous studies have commonly included only one breed of horse and considered only one hard, concrete-like flooring.

Thus, this research aimed to propose IMU based methods of gait event detection, exploring different sensor locations and exercise surfaces, testing methods on a highly varied cohort of horses, and validate them against current state-of-the-art methods which use hoof-mounted IMUs. This will facilitate future studies under a variety of field conditions.

3.2 Materials and methods

3.2.1 Horses

Eleven horses were included in this study. These were eight geldings (castrated males) and three mares (females), of mean and standard deviation (sd) heights 154(21)cm and ages 12(8)years) of various breeds and levels of training and fitness, from retired ponies and horses used for hacking (general riding for pleasure or exercise which is not necessarily sport-specific training) to top level event horses (Table 3.1). Eight horses were shod and three were not.

Table 3.1 details of subject population including if horse was shod (y) or not (n) and the usual use of the horse; ISH=Irish Sports Horse; Welsh C=Welsh Section C.

Horse	Breed/type	Height (cm)	Age (years)	Shod (y/n)	Usual use
1	Selle français	158	11	y	Low level eventing
2	ISH	166	13	y	5* eventing
3	ISH	147	20	y	Low level eventing
4	Friesian	158	4	y	Hacking
5	Westfalian	168	7	y	Low level eventing
6	ISH	168	14	y	2* eventing
7	Shetland	91	30	n	Retired
8	ISH	168	6	y	Low level eventing
9	Cob	150	12	n	Hacking
10	Welsh C	149	16	n	Low level dressage
11	ISH	166	5	y	Low level eventing
mean(sd)	-	154(21)	12(8)	-	-

3.2.2 Data acquisition

Six IMUs (Shimmer3 IMU) were used to record data at 200Hz. Sensors were attached laterally to the hooves and the regions of the pasterns (proximal phalanges) and cannon bones (third metacarpal and tarsal bones) (Fig 3.1) of the left fore and hindlimbs. Gyroscopes and magnetometers recorded data ranges of ±2000°/s and ±49Ga, respectively, and the triaxial accelerometers of ±16g at the cannons and ±200g at the pasterns and hooves, where g is the acceleration due to gravity (9.81m/s^2). Cannon sensors were attached using commercially available pockets (Estride™, Bognor Regis, UK), pastern IMUs using hook-and-loop wraps and tape, and hoof IMUs using tape and elasticated bandages.

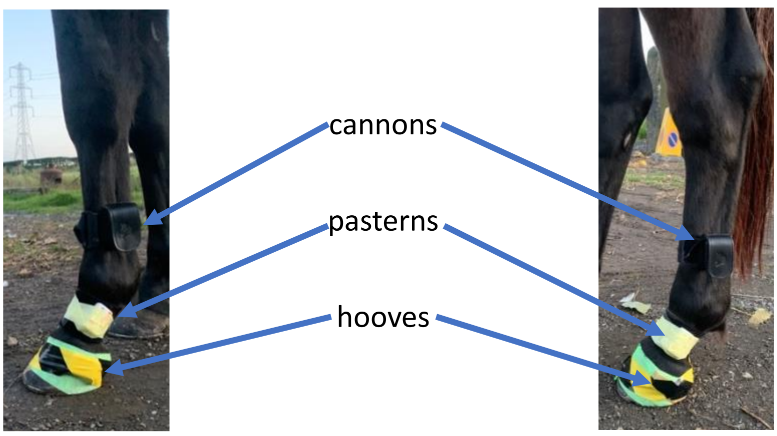


Figure 3.1 IMU placement.

Each horse was led by an experienced handler in a straight-line of 35m at walk and trot, three passes per gait, on a hard control surface (asphalt). To ensure steady gait was analysed, the central 25m of the trial were used in the data processing stages. Trials were repeated on a grass field (grass) and sand and rubber chip surface (sand). Efforts were made to ensure data was recorded under similar conditions for all horses- all surfaces were level and datasets were collected during periods of dry weather when the grass field would be firm and the sand soft. Horses were verbally encouraged to maintain the correct gait (walk or trot) but were allowed to move at self-selected speeds. The methods were reviewed and approved by The University of Sheffield, Ethics Department (Reference Number 033398), and horse owners gave signed consent for their animal's involvement.

3.2.3 Gait events detection

The gait events (recall Chapter 1, Fig 1.4) were defined as the instants in the stride cycles when the hoof first comes into contact with the ground at the onset of the stance phase (hoof-on) and when it is lifted from the ground, following breakover (hoof-off)[174]. A stride cycle refers to one full cycle of gait, from one hoof-on to the subsequent hoof-on of the same limb. In the data processing stages, the timings of gait events were estimated using various processing methods and data from different sensor locations. Algorithms were developed in Matlab (version 2020R, The MathWorks Inc., Natick, Massachusetts, USA).

3.2.3.1 Reference method

Data from the IMUs mounted on the lateral hoof walls were processed as per Tijssen et al.[196] and gait event timings determined using this method (M_{ref}) were used as the *ground-truth*, reference values against which to compare those obtained using other methods. This method was previously validated for one hard surface against the timing of events detected using a force plate for fore and hindlimbs at walk and trot. Accuracies of 2.39-12.22ms for the hoof-on and 3.2ms for the hoof-off events were reported. Briefly, M_{ref} assumes that prominent peaks in the resultants of angular velocity (ω_R) and acceleration (Acc_R) measured at the level of the hoof correspond to instants of hoof-on (Fig 3.2G, down triangles) and -off (Fig 3.2H, up triangles), respectively.

3.2.3.2 Alternative methods

The first novel method estimated hoof-on and -off using Acc_R of either the cannon ($M1_c$, Fig 3.2 A and B) or pastern ($M1_p$, Fig 3.2 C and D). At the level of the hoof, peaks in Acc_R are created by the hoof-surface impact (hoof-on) and subsequent hoof lift-off (hoof-off)[196]. Here, it is hypothesised that these peaks in acceleration, which correspond to the gait events, would be detectable at the more proximal locations of the pasterns and cannons.

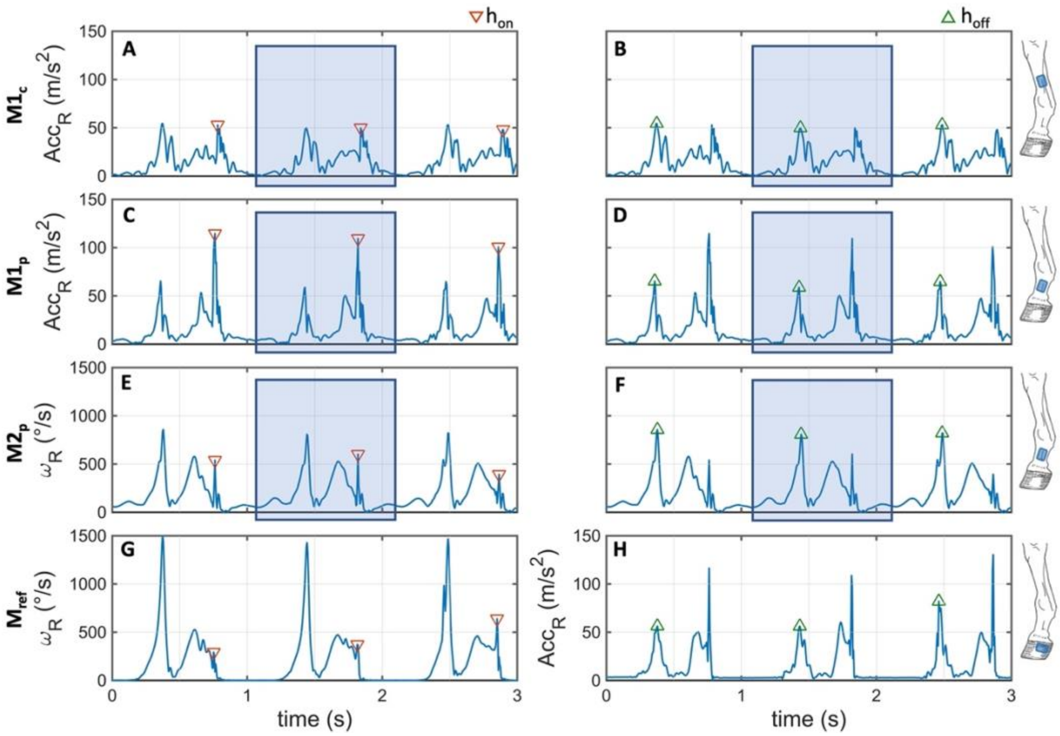


Figure 3.2 illustration of the different methods of gait event detection. Hoof-on (h_{on}, red down triangles) and -off (h_{off}, green up triangles) events detected by novel method M1 applied to resultant accelerations (Acc_R) recorded from the cannons ($M1_c$, A and E) and pasterns ($M1_p$, B and F); and by novel method M2 applied to resultant angular velocity (ω_R) recorded from pasterns ($M2_p$, E and F) are illustrated. The hoof-based reference method is illustrated (M_{ref}, G and H). These signals were collected concurrently from IMUs attached to the forelimb of Horse 9 at walk on asphalt. The blue windows (A-F) illustrated how data was first segmented into periods of midstance to midstance. For further examples of signals collected at walk and trot from fore and hindlimbs on asphalt, grass and sand, see 3.6 Appendix.

$M1_p$ and $M1_c$ were applied for fore and hindlimbs at walk and trot. To assist in the subsequent peak detection, Acc_R was first segmented into rough periods of midstance to midstance (an example is given by blue windows in each of Fig 3.2A to

D). To achieve this for walk, a 1D median filter[258] with window length of half the sampling frequency (100 frames) followed by a 2nd order Butterworth filter with cut off frequency of 5Hz was used to identify rough locations of the swing and stance periods. For trot, the same median filter followed by a 2nd order Butterworth, low-pass filter with 20Hz cut off frequency was applied to the hindlimb cannon data, whereas a Butterworth, low-pass filter with 5Hz cut off frequency, alone, was used for all other trot cases. The raw Acc_R was then filtered with a 2nd order Butterworth, low-pass filter with cut off frequency 40Hz and the tallest peak in the first half of the window (Fig 3.2B and D, up triangles) and tallest in the second half of the window (Fig 3.2A and C, down triangles) were labelled as hoof-off and -on, respectively.

The second novel method estimated hoof-on and -off using ω_R recorded by the pastern-mounted sensors ($M2_p$, Fig 3.2 E and F). Tijssen et al.[196] reported that spikes in ω_R recorded at the hoof coincide with hoof-on and -off. Here, the hoof wall can be considered a rigid structure meaning there would be no angular movement of the hoof relative to the solid ground during stance phases. Hence, peaks in ω_R before and after the stance duration, where the signal is quite flat, coincide with hoof-on and -off (Fig 3.2G). On this premise, it was hypothesised that a peak corresponding to the gait events would also be detectable in ω_R at the level of the pasterns.

$M2_p$ was applied for the fore and hindlimbs at walk and trot. After using the same windowing method described for M1 to the ω_R signal, but with median filter window length of one eighth the sampling frequency (25 samples) (Fig 3.2E and F, blue windows), the raw ω_R was filtered using a second order Butterworth filter, cut off frequency 40Hz. The tallest peak in the first half of the window (Fig 3.2F, up triangles) and the last peak in the window which was $\geq$30% the height of that tallest peak (Fig 3.2E, down triangles) were detected and labelled hoof-off and -on, respectively.

Two additional methods, taken from the literature, were also investigated. Method $M3_c$ estimates hoof-on and -off using the angular velocity measured at the cannon[195]. The raw component of angular velocity about the sensor axis aligned with the mediolateral direction of the horse (ω_{ML}) recorded from a cannon-mounted sensor is used. This method had been previously validated against a motion capture system for detecting gait events from the forelimb at trot on a hard surface (Fig 3.3C); the deepest trough following the large peak of the signal is used to identify the hoof-on (down triangles) and the first peak to occur after the relatively flat (stance) portion to identify the hoof-off (up triangles). In the present study, the method was also applied to data from the hindlimbs and walk, with adjustments made owing to the different ω_{ML} signal profiles produced by the different limb and gaits. For each limb and gait, the biggest peak in the signal was observed during the swing. For the hind limbs at trot (Fig 3.3D), the deepest trough following this large peak was again detected as the moment of hoof-on and the last peak before it as hoof-off. For the forelimb at walk (Fig 3.3A), the deepest troughs before and after the large peak, respectively, were detected as instants of hoof-off and -on. For the hindlimbs at walk (Fig 3.3B), the deepest trough after the large peak was taken as the time of hoof-on and the last peak before it as the time of hoof-off.

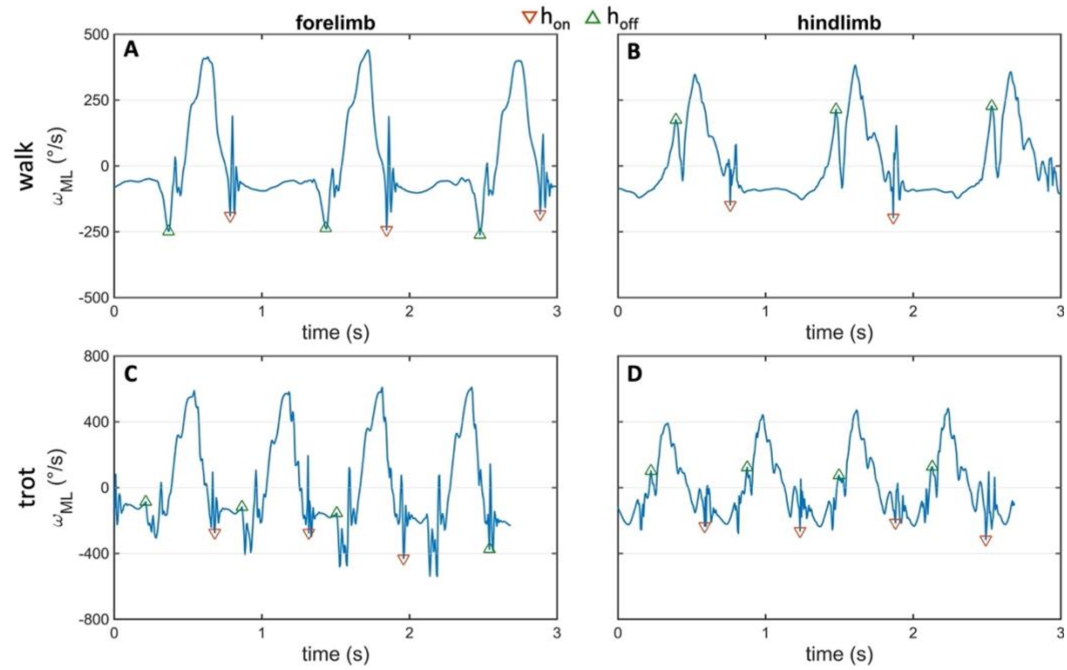


Figure 3.3 illustration of $M3_c$ for each limb (fore and hind) and gait (walk and trot); hoof-on and -off events are indicated by red down triangles and green up triangles, respectively.

Method $M4_c$[194] was applied to estimate hoof-on and -off from orientation and acceleration cannon data at walk and trot for fore and hindlimbs, for which it was previously validated on a hard surface against force plate methods. First, the sensor angles were calculated using the IMUs' proprietary software (ConsensysPRO, Shimmer Sensing, Dublin, Ireland). The timings of mid-swing and -stance points were estimated form these angles and these were then used to assist in detection of peaks corresponding to hoof-on and -off events in the Acc_R[76].

3.2.4 Data analysis

3.2.4.1 Quantification of errors in event detection

Descriptive statistics and agreement were calculated in Matlab. Initial analysis was conducted only on data recorded on the control surface- asphalt- which was considered the reference surface as this was the surface most like that on which the reference method of gait event detection[196] was validated. Errors (e_{on} and e_{off}) were calculated (Eq 3.1 and 3.2) by comparing the timing of hoof-on and -off events detected by the reference method ($h_{on_{ref}}$and $h_{off_{ref}}$) to those detected by each alternative method ($h_{on_{alt}}$and $h_{off_{alt}}$), in turn.

$$e_{on} = h_{on_{ref}} - h_{on_{alt}} \qquad (3.1)$$

$$e_{off} = h_{off_{ref}} - h_{off_{alt}} \qquad (3.2)$$

For individual gait events, errors were expressed in ms and the performance of each method was assessed in terms of accuracy and precision, where accuracy was defined as the mean of the errors (Eq 3.3 $E_{on_{\mu}}$ and Eq 3.4 $E_{off_{\mu}}$) incurred by the method and precision as the standard deviations of these errors. Methods were considered superior if the values of accuracy and precision were low, indicating a low mean error and small distribution of the error.

$$E_{on_{\mu}} = \frac{1}{n}\sum_{i=1}^{n}(e_{on})_i \qquad (3.3)$$

$$E_{off_{\mu}} = \frac{1}{n}\sum_{i=1}^{n}(e_{off})_i \qquad (3.4)$$

Gait events detected by each method were used to calculate stride durations and the agreement of each with those calculated using the reference method was quantified by the intraclass correlation coefficient for interrater reliability, ICC{3,1}[259], and limits of agreement (LoA), with upper and lower limits of agreement (ULoA and LLoA) calculated as per Bland and Altman[260] (Eq 3.5 and 3.6). This involved calculating the mean error in stride duration ($\mathrm{E}_{\mathrm{stride}_{\mu}}$) and standard deviation of the errors ($\mathrm{E}_{\mathrm{stride}_{\sigma}}$). Incurrences of false positive (FP), false negative (FN) and true positive (TP) events were detected and used to calculate sensitivity (Eq 3.7) and positive predictive value (PPV) (Eq 3.8)[261].

$$\mathrm{ULoA} = \mathrm{E}_{\mathrm{stride}_{\mu}} + 1.96 \cdot \mathrm{E}_{\mathrm{stride}_{\sigma}} \quad (3.5)$$

$$\mathrm{LLoA} = \mathrm{E}_{\mathrm{stride}_{\mu}} - 1.96 \cdot \mathrm{E}_{\mathrm{stride}_{\sigma}} \quad (3.6)$$

$$\mathrm{sensitivity} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}} \cdot 100 \quad (3.7)$$

$$\mathrm{PPV} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FP}} \cdot 100 \quad (3.8)$$

Statistical analysis was carried out in IBM SPSS Statistics V27.0 (Armonk, NY), with p-values <0.01 indicating significance. Normality of the error data was first evaluated using Shapiro-Wilks test and by visual appraisal of the Q-Q plots. Differences between mean errors (Eq 3.3, $\mathrm{E}_{\mathrm{on}_{\mu}}$ for hoof-on detection; Eq 3.4, $\mathrm{E}_{\mathrm{off}_{\mu}}$ for hoof-off) for $M1_p$, $M2_p$ and $M1_c$ were then tested for significance. Where normality was upheld, a one-way repeated measures ANOVA, controlled for the covariate individual horse, was conducted and Bonferroni post hoc test used to identify the source of significance, if any were found. If a dataset violated the assumption of homogeneity of variance, the Games-Howell post hoc test was used. Where normality was violated, differences were tested for significance using a Friedman test and Wilcoxon Signed Rank post hoc test, if significant differences were identified.

3.2.4.2 Comparison between different surfaces

After the most accurate and precise methods were identified for each gait event on the control surface (asphalt), they were then used to detect gait events for data collected on the additional surfaces (grass and sand). From these gait events, the stance durations (time from hoof-on to subsequent hoof-off) were calculated for the fore and hindlimbs at walk and trot on each surface, using Eq 1.2.

Each stance calculated using the novel method (t_{alt}) was compared to that obtained by the reference method (t_{ref}) by Eq 3.9 to obtain a value of error (e_{stance}).

$$e_{stance} = t_{ref} - t_{alt} \qquad (3.9)$$

Bland-Altman methods were used to investigate the effect of different surfaces on the error incurred in stance calculation. Errors were expressed as percentages of the total stride duration and analysed as Bland-Altman figures, with e_{stance} plotted against t_{mean}, the mean of t_{ref} and t_{alt} (Eq 3.10).

$$t_{mean} = \frac{t_{ref}+t_{alt}}{2} \qquad (3.10)$$

The difference in mean error incurred for stance calculation (Eq 3.11, $E_{stance_{\mu}}$), as a percentage of stride duration and stance duration, for each limb and gait, on each of the three surfaces were compared using a repeated measures one-way ANOVA or Friedman test, depending on the result of a Shapiro-Wilks test for normality and consideration of the Q-Q plots. Again, where significant differences were detected, Bonferroni or Wilcoxon signed rank post hoc tests were used. The effect of the individual horse covariate was controlled.

$$E_{stance_{\mu}} = \frac{1}{n}\sum_{i=1}^{n}(e_{stance})_i \qquad (3.11)$$

3.3 Results

A total of 1465 walk and 1255 trot strides were analysed. These were 500, 535 and 430 walk strides and 438, 399 and 418 trot strides on asphalt, sand and grass, respectively.

3.3.1 Event detection

The accuracies and precisions (mean and sd, as per previous definition) of the methods to detect gait events (Fig 3.4) and agreement (LoA and ICC) with the reference method are given in ms (Table 3.2).

For the cannon data, $M1_c$ performed better than $M3_c$ and $M4_c$, in all cases (Fig 3.4E-H and M-P). The values of ICC (Table 3.2) showed excellent agreement for all uses of $M1_p$, $M2_p$, $M1_c$ and $M3_c$ with M_{ref} to calculate stride durations (ICC>0.90). Agreement for $M4_c$ was not consistently excellent, with the poorest value (ICC=0.554) occurring for hindlimb hoof-on events at trot. The poor agreements seen for $M4_c$, along with the high mean errors and sd, led to exclusion of the method from further analysis.

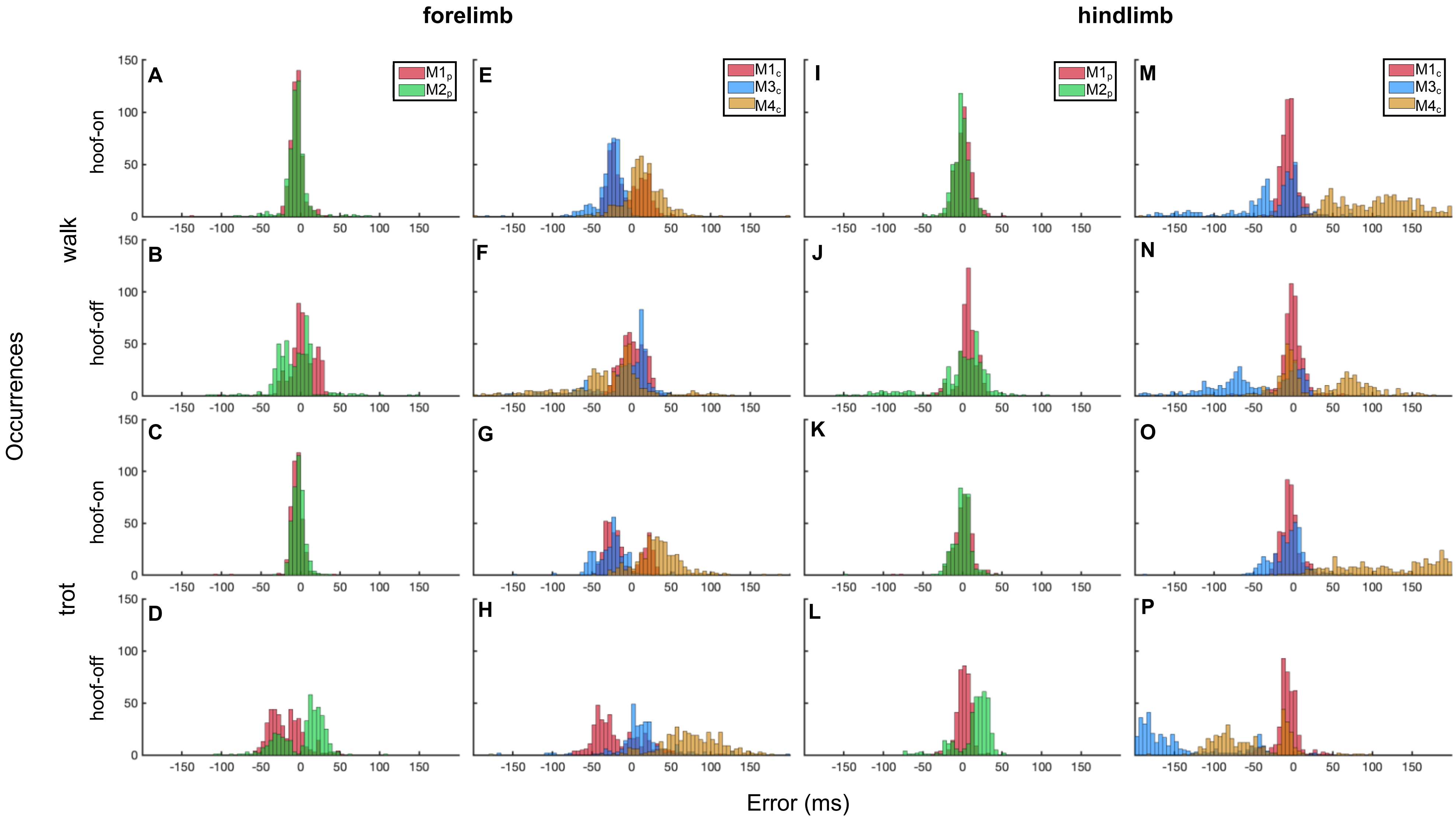


Figure 3.4 histograms demonstrating the distribution of the errors (ms) incurred by methods to detect fore and hindlimb hoof-on and -off events at walk and trot.

*Table 3.2 errors (ms) incurred by each method to detect gait events and agreement with M_{ref} for calculating stride durations (ICC); superscripts *,^ and † indicate where the difference between two mean errors was statistically significant ($p<0.01$); sensitivity and positive predictive values (PPV) are given as percentages of the total number of events detected; for each gait event, the best performing method is bold.*

(ms)			method	mean	sd	LLoA	ULoA	ICC	sensitivity (%)	PPV (%)
					forelimb					
walk	hoof-on	Pastern	**M1**	**-5**	**11**	**-26**	**16**	**0.998**	**100**	**99**
			M2	-4	14	-33	24	0.995	99	99
		Cannon	M1	-5	21	-47	37	0.991	100	97
			M3	-30	40	-109	49	0.968	100	93
			M4	14	72	-127	155	0.925	90	100
	hoof-off	Pastern	**M1**	**3**	**16**	**-28**	**34**	**0.996**	**100**	**99**
			M2	-7	27	-61	46	0.988	99	99
		Cannon	**M1**	**1**	**19**	**-36**	**38**	**0.994**	**100**	**97**
			M3	-15	65	-142	112	0.929	100	93
			M4	-35	117	-265	194	0.846	90	100
Trot	hoof-on	Pastern	M1	-4*,^	10	-24	15	0.991	99	99
			M2	**-2 *,†**	**9**	**-19**	**15**	**0.994**	**99**	**99**
		Cannon	M1	-9^,†	23	-55	37	0.952	99	100
			M3	-26	21	-67	16	0.957	100	94
			M4	43	67	-89	175	0.834	81	100
	hoof-off	Pastern	M1	-18*	23	-62	27	0.958	99	99
			M2	**4*,†**	**34**	**-63**	**71**	**0.937**	**99**	**99**
		Cannon	M1	-15†	33	-80	50	0.934	99	100
			M3	62	114	-231	218	0.956	100	94
			M4	77	102	-123	277	0.737	81	100
					hindlimb					
walk	hoof-on	Pastern	**M1**	**2*,^**	**10**	**-19**	**22**	**0.997**	**100**	**100**
			M2	-1*,†	10	-22	19	0.998	99	100
		Cannon	M1	-5^,†	11	-26	17	0.998	100	99
			M3	-31	55	-139	77	0.946	100	97
			M4	161	412	-652	974	0.701	90	100
	hoof-off	Pastern	**M1**	**6^**	**14**	**-22**	**34**	**0.993**	**100**	**100**
			M2	-3†	38	-77	72	0.960	99	100
		Cannon	**M1**	**-1^,†**	**15**	**-29**	**28**	**0.994**	**100**	**99**
			M3	-57	69	-292	77	0.928	100	97
			M4	-15	180	-368	338	0.700	90	100
trot	hoof-on	Pastern	**M1**	**1*,^**	**12**	**-23**	**26**	**0.995**	**99**	**100**
			M2	-1*,†	19	-37	36	0.988	99	100
		Cannon	M1	-3^,†	16	-34	29	0.986	96	100
			M3	-4	27	-56	48	0.963	100	97
			M4	98	147	-190	387	0.544	90	100
	hoof-off	Pastern	**M1**	**2*,^**	**9**	**-16**	**20**	**0.997**	**99**	**100**
			M2	15*, †	21	-26	57	0.977	99	100
		Cannon	M1	-7^,†	14	-35	22	0.988	96	100
			M3	-144	62	-264	-23	0.913	100	97
			M4	-72	100	-267	124	0.640	90	100

For pastern data, $M1_p$ and $M2_p$ both performed well for detecting all gait events (Fig 3.4A-D and I-L). $M1_p$ generally outperformed $M2_p$, except in the case of the forelimb events at trot, where $M2_p$ incurred a significantly smaller mean error ($p=0.005$, hoof-on, Fig 3.4C; and $p<0.001$, hoof-off, Fig 3.4D). For hindlimb hoof-on events (Fig 3.4K), the two methods were equally successful with $M1_p$ detecting events slightly late by a mean(sd) delay of 2(10)ms, and $M2_p$ slightly early, -1(10)ms. $M1_p$ was generally more successful than $M1_c$ except in the case of hoof-off events at walk ($p=0.130$, forelimb, Fig 3.4B and F; and $p<0.001$, hindlimb, Fig 3.4J and N). For the novel methods, no significant between-horses effects were found ($p>0.9$).

Overall, the pasterns appear to be a superior location for sensor attachment than the cannons. In terms of reliability, pastern methods consistently achieved sensitivity and PPV values of 99 or 100%. $M1_p$ was identified as the better method for detecting all gait events except forelimb events at trot, for which $M2_p$ demonstrated better accuracy. Furthermore, in all cases except for hoof-on forelimbs at trot, the LoA of $M1_p$ were consistently narrower than for any other method. For hoof-on of the forelimbs at trot, $M2_p$ yielded the narrowest LoA.

For the next level of analysis, where the stance durations on all three surfaces were calculated using the reference and novel method, $M2_p$ was used to detect the gait events for the forelimbs at trot and $M1_p$ was used for all other cases.

3.3.2 Comparison between surfaces

The errors incurred in stance durations for asphalt, grass and sand are summarised in Table 3.3 as percentages of total stride duration and Table 3.4 as a percentage of stance duration.

*Table 3.3 descriptive statistics of errors (**as % of stride**) incurred by best methods to calculate stance duration on each surface; superscripts indicate where two means differed significantly ($^{a}p<0.01$ and $^{b}p<0.001$) as revealed by post hoc tests.*

(%)	surface	method	mean	sd	LLoA	ULoA	sensitivity (%)	PPV (%)
			forelimb					
	Asphalt	$M1_p$	0.92	2.98	-4.92	6.76	100	99
walk	Grass	$M1_p$	0.52	2.14	-3.67	4.71	98	99
	Sand	$M1_p$	1.19	5.29	-9.18	11.56	100	97
	Asphalt	$M2_p$	$1.09^{a,b}$	8.68	-15.92	18.10	99	100
trot	Grass	$M2_p$	-0.57^{a}	6.67	-13.64	12.50	100	100
	Sand	$M2_p$	-1.09^{b}	7.68	-16.14	13.96	99	100
			hindlimb					
	Asphalt	$M1_p$	0.10	3.42	-6.60	6.80	100	100
walk	Grass	$M1_p$	-0.33	7.42	-14.87	14.21	99	100
	Sand	$M1_p$	0.22	3.60	-6.84	7.28	99	98
	Asphalt	$M1_p$	0.50	2.38	-4.16	5.16	99	99
trot	Grass	$M1_p$	0.92	2.26	-3.51	5.35	97	100
	Sand	$M1_p$	1.16	4.28	-7.23	9.55	98	100

*Table 3.4 descriptive statistics of errors (**as % of stance**) incurred by best methods to calculate stance duration on each surface; superscripts indicate where two means differed significantly ($^{a}p<0.001$ and $^{b}p<0.001$) as revealed by post hoc tests.*

(%)	surface	method	mean	sd	LLoA	ULoA	sensitivity (%)	PPV (%)
			forelimb					
	Asphalt	$M1_p$	1.03	2.39	-3.66	5.72	100	99
walk	Grass	$M1_p$	0.85	3.09	-5.21	6.91	98	99
	Sand	$M1_p$	0.67	3.64	-6.46	7.81	100	97
	Asphalt	$M2_p$	2.42^{a}	11.11	-19.35	24.2	99	100
trot	Grass	$M2_p$	$-0.26^{a,b}$	10.05	-19.96	19.44	100	100
	Sand	$M2_p$	-1.05^{b}	10.64	-21.91	19.81	99	100
			hindlimb					
	Asphalt	$M1_p$	-2.32	9.92	-21.77	17.13	100	100
walk	Grass	$M1_p$	7.27	14.99	-22.12	36.65	99	100
	Sand	$M1_p$	-7.29	14.32	-35.36	20.79	99	98
	Asphalt	$M1_p$	$3.47^{a,b}$	10.74	-17.57	24.51	99	99
trot	Grass	$M1_p$	2.36^{a}	16.6	-30.18	34.9	97	100
	Sand	$M1_p$	2.23^{b}	10.25	-17.87	22.33	98	100

Reliability of the pastern methods remained high when applied to the additional surfaces, maintaining sensitivity and PPV values of 97% and above. In terms of bias (mean error), $M1_p$ performed equally well when applied to the additional surfaces as well as asphalt and small variations in mean were not statistically significant. Furthermore, LoA were generally within ±10%, except in the case of hindlimb walk on grass, where the LoA were -15-14%. These LoA were similarly wide to those for stance durations calculated using $M2_p$ (for forelimbs at trot), where they ranged from -14-13% on grass to -16-18% on asphalt. $M2_p$ performed marginally better on grass and sand compared to the control surface, in terms of bias and sd, for calculating stance durations of the forelimbs at trot. These stance durations were generally the least precise (ranging from 6.67-8.68%), with only the hindlimbs at walk on grass having a comparable sd (7.42%).

Results of the Bland-Altman analysis are shown in Fig 3.5. The mean error and LoA (shown as 95% confidence limits) were calculated after pooling together stance durations on all three surfaces. Although the LoA calculated in this way, were wider in most cases than for each of the three surfaces considered individually, the mean error remained close to 0% and LoA only exceeded 10% for the forelimbs at trot (Fig 3.5B). The higher LoA in the latter case are reflective of the higher values of sd (Table 3.3). As with event detection on asphalt, no significant between-horses effects were seen ($p>0.8$), suggesting methods had the same performance for all individuals.

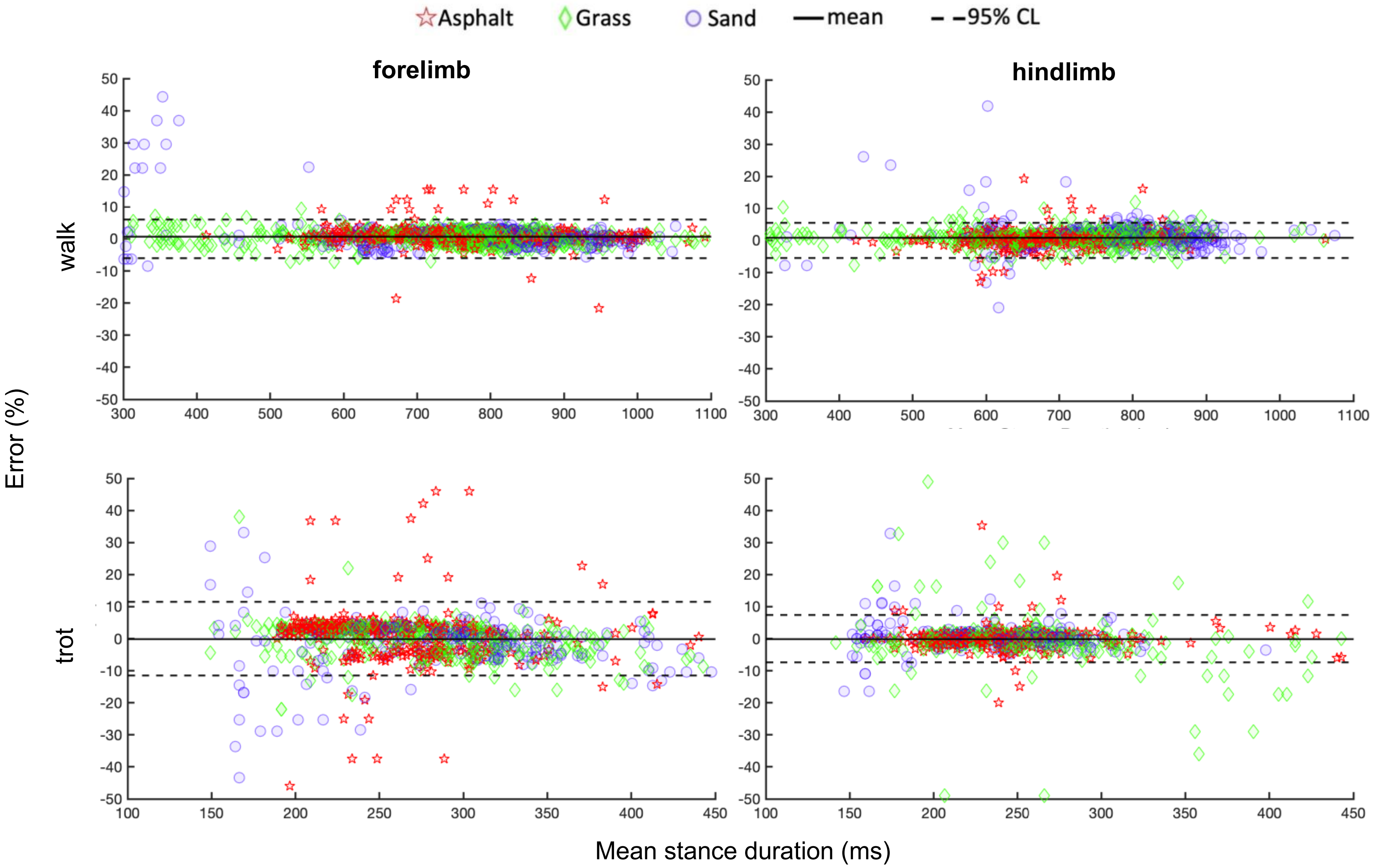


Figure 3.5 Bland-Altman plots showing difference between stance duration calculated using reference method and best novel method (as % of stride duration) as a function of the mean of the two. Data points calculated from asphalt are shown as red stars, from grass as green diamonds and from sand as blue circles. Each datapoint represents one measure of stance duration

3.4 Discussion

The aim of this research was to propose and test different methods of gait event detection using IMUs. Both different sensor locations and signal processing techniques were explored and validated against a current state of the methods which used hoof-mounted IMUs. Overall, the best results were obtained from the pastern sensor using an algorithm based on the analysis of the resultant acceleration ($M1_p$), with the only exception being the forelimbs at trot, where angular velocity ($M2_p$) was shown to be preferable. These methods proved superior to those cannon-based ones previously introduced in the literature ($M3_c$ and $M4_c$). Next, the study proved that pastern-based methods also showed good agreement with the hoof-based, for data recorded on the additional surfaces of grass and sand. No strong conclusions as to how accurate and precise the novel methods were when applied to data collected on the additional surfaces can be drawn as the reference, hoof-based method was only previously validated for use on hard surfaces.

3.4.1 Event detection

Cannon-based methods, as previously proposed in the literature, proved to be accurate but not precise at walk and less accurate at trot, despite having been validated under this condition. $M3_c$ errors in detecting forelimb hoof-on and -off events, were -30ms and -15ms respectively at walk, and -26ms and 62ms at trot. For hindlimb hoof-on events, similar errors were found at walk (-31ms) and smaller errors at trot (-4ms). However, larger errors were observed for hoof-off events for the hindlimb at both walk (-57ms) and trot (-144ms). These high inaccuracies could be due to using the ω_{ML} signal alone, which may be heavily dependent on the exact orientation of the sensor. Hence, the method may not be as robust, compared to other methods, under field conditions where some degree of sensor movement relative to the horse is inevitable. Indeed, $M1_c$, which uses only resultant accelerations and is as such more robust to changes in sensor orientation, was more accurate and precise than either, $M3_c$ or $M4_c$. Furthermore, it also outperformed them in terms of sensitivity and PPV, consistently achieving values of 96% and higher compared to 93% for $M3_c$ and 81% for $M4_c$. $M4_c$ always recorded the lowest value of sensitivity (ranging from 81 to 90%), indicating that this method tended to miss gait events. Similarly, $M3_c$ incurred the lowest values of PPV in all cases (ranging from 93 to 97%), indicating that this method tended to erroneously detect additional gait events where there were none. It may be that for these two methods that the initial step of stride identification failed in some cases. The low values of sensitivity and PPV may also go some way towards explain the high mean errors incurred for these methods. For all gait event types, $M4_c$ recorded the lowest values of ICC and in all cases but for the hoof-on and -off of the forelimbs at trot, $M3_c$ recorded the second lowest values of ICC.

The errors incurred by $M3_c$ and $M4_c$ in this study were substantially larger than those reported in the literature. In the source paper, $M3_c$ was reported to incur a bias of 0.6% and 0.1% of a stride cycle for forelimb hoof-on and -off events at trot[195]. In the present application, for hoof-on and -off the method incurred errors of -26ms and 62ms, respectively, equivalent to -3% and 7% of a stride cycle, some 5 and 70 times greater than in the original source. $M4_c$ was reported to incur mean errors ranging from -5.4ms to 14.2ms[194], far lower than those observed here (-72ms to 161ms). Several reasons for these substantial differences could be suggested. Firstly, in the present study, a highly varied cohort of horses was recruited and both fore and hindlimbs tested. In comparison, $M3_c$ had only previously been validated for the forelimbs of trotters at trot and $M4_c$ only for Warmblood horses. The different gait styles adopted by different horses may be partly responsible for the difference in accuracies[254]. The difference in reference methods used in the various studies may have also contributed to the difference in errors. Further studies, based on the same gold standard, would be needed to verify this hypothesis. Overall, according to the above considerations, the novel method M1 is recommended when using data collected at the cannon.

Applications of the novel methods M1 and M2 to the pastern data led to even better results than those found for the cannon. For most events, although the average errors were similar in many cases, the distribution of the error was usually smaller for $M1_p$ than $M1_c$. In fact, $M1_c$ performed better than $M1_p$ in only one case- hindlimb hoof-off at walk. Here, the standard deviations (14ms for $M1_p$; 15ms for $M1_c$) and

LoA (-22-34ms for $M1_p$; -29-28ms for $M1_c$) were both similar but magnitude of the mean error was 5ms bigger for the pastern data (6ms compared to 1ms). This difference was statistically significant but a 5ms (<0.5% of a stride duration) difference is only marginal. Furthermore, the LoA for M1 applied to the pasterns for forelimb hoof-off at walk, were narrower (-28 and 34ms) than those incurred for the same method applied to the cannons (-36 and 38ms). In light of the difference in mean error being very small, the narrower LoA for $M1_p$ and the convenience of having only one site of sensor placement for all events, the pastern was deemed the best location at which to record data for gait event detection.

The higher precision of $M1_p$ is likely due to the pasterns being closer to the site of hoof impact and lift-off than the cannons. The acceleration peaks resulting from the gait events are expected to be less attenuated at the level of the pasterns, compared to the cannons, thus reducing the chances of the peak of interest becoming lost in noise. Indeed, it was previously reported that 21% of the initial impact vibration of the forelimb hoof-on remains after the junction of the middle and proximal phalanx, where the pastern sensor was mounted, compared to only 13% after the junction of the proximal phalanx and third metacarpal, where the cannon sensor was[262].

The superiority of acceleration-based methods was confirmed by comparison between $M1_p$ and $M2_p$, the latter tending to perform slightly worse for most events, despite retaining good accuracy (-7 to 15ms) and precision (9 to 38ms) overall. Furthermore, $M1_p$ yielded the narrowest LoA in all cases except for that of the forelimb hoof-on events at trot, further emphasising its advantage over the alternative methods for detection of most gait events. The only cases in which $M2_p$ was more accurate than $M1_p$ was at trot for forelimb hoof-on (-2ms compared to -4ms) and -off (4ms compared to -18ms). For the forelimb hoof-on at trot, $M2_p$ was marginally more precise than $M1_p$ (with a sd of 9ms compared to 10ms), with narrower LoA (-19 and 15ms compared to -24 and 15ms). However, for the hoof-off events of the forelimbs at trot, the precision of $M2_p$ was notably lower (34ms compared to 23ms) than that of $M1_p$ and the LoA were considerably wider (-63 and 71ms compared to -62y 27ms). These wide LoA for $M2_p$'s detection of forelimb hoof-off events at trot reflect the bimodal nature of the error distribution (Fig 3.4D). Thus, although here $M2_p$ is chosen as the better method for forelimb hoof-off detection at trot due to the magnitude of the mean error being 4.5 times smaller, care must be exercised when using the method to detect such events in the future. In summary, considering errors incurred for event detection, $M2_p$ is recommended for calculating forelimb stance durations at trot and $M1_p$ for all other cases.

It has previously been reported that mild and moderate forelimb lameness can cause reductions in trot stride duration of 11ms and 31ms, respectively[201]. The mean errors incurred by the described pastern-based methods (ranging in magnitude from 1ms for hindlimb hoof-on events to 4ms for the forelimb hoof-off events) suggest that any of the gait events could be used to measure such changes. However, the LoA must also be taken into consideration. The narrowest LoA for detecting gait events at trot were those recorded for the forelimb hoof-on events (-19 to 15ms, a range of 34ms); hence, it is advisable to use these gait events for calculating stride durations at trot. Considering these LoA, the methods appear to be insufficient for detecting changes of stride duration due to mild lameness (11ms) but may be useful for detecting those due to moderate lameness (31ms), although caution should be exercised, as the range of the LoA is actually 3ms larger than this value.

One application for which the methods are certainly accurate enough is for measuring changes in stride duration with maturation. The stride duration of horses trotting on a treadmill was found to increase from 620ms when they were measured at 4 months of age to 670ms when they were 26 months[263], an increase of 50ms. Using the forelimb hoof-on events (LoA -19 and 15ms) or hindlimb hoof-on (LoA -23 and 26ms) or -off (LoA -23 and 26ms), changes of this magnitude could be measured using the proposed pastern-based methods.

In thirteen Icelandic horses, the stride duration of the trot was found to increase from 574ms when the horses were shod in the conventional manner to 589ms when they were shod with long and high forelimb hooves for competition, an increase of 15ms[264]. Again, the mean(sd) error incurred by the pastern-based methods for detecting hoof-on events of the fore (-2(9)ms) and hindlimbs (1(12)ms) at trot indicate that they are accurate enough to detect such changes. As the errors appear to be normally distributed (Fig 3.4 C and K), this may be the case but the LoA are wider than this difference in both cases (-19 and 15ms forelimbs; -23 and 26ms hindlimbs) and, hence, caution should be exercised when using the methods for such an application.

3.4.2 Comparison between surfaces

Next, methods were used to detect gait events on the additional surfaces of grass and sand. As the reference, hoof-based method[196] had previously only been validated for hard surfaces, use of the novel methods on the additional surfaces can only be evaluated in terms of how well they agreed with the results obtained using the hoof-based method. Previous literature had found that data recorded on hard and soft surfaces using accelerometers attached to the hooves yielded signals with similar profiles, from which the gait events could be manually extracted[174]. Visual inspection of the signals recorded in the present study verified that those recorded on the hard surface (asphalt) had a similar profile to those collected on the additional surfaces of grass and sand, with similar peaks prominent (for examples, see 3.6 Appendix). Hence, the assumption that the hoof-based method could be used to record data on the two additional surfaces seemed justifiable.

Using $M1_p$ and $M2_p$ as recommended, stance durations on asphalt were calculated with a very high level of accuracy (ranging from 0.1% to 1.09% of a stride duration), which was markedly more accurate than those reported in the literature on an equivalently hard surface (laboratory), which ranged from -0.8% of a stride duration for the hindlimbs at walk to 9.1% for the hindlimbs at trot[194].

In the literature, it was reported that unilateral forelimb lameness increased the stance phase of both forelimbs by 2.3% and that of the ipsilateral hindlimb by 1.3% for horses trotting on a treadmill[51] (a hard surface). The mean error in trotting stance durations calculated using the described methods were 1.09% of a stride duration for the forelimbs and 0.5% for the hindlimbs at trot. Hence, the mean errors suggest that the presented methods would be sufficient for characterising such changes. However, also considering the LoA, (-16 to 18% of a stride duration for forelimbs and

-4 to 5% for hindlimbs,) in practice the methods may not be dependable for detecting such small lameness-dependent changes in stance phase duration.

When $M1_p$ and $M2_p$ were used as recommended to calculate stance durations on the additional surfaces, the magnitude of the mean errors remained low (ranging from 0.22(3.6)% for the hindlimbs at walk on sand to 1.19(5.29)% for the forelimbs at walk on sand). This indicates that the methods generally showed good agreement with the hoof-based, reference method. Furthermore, the LoA recorded for each gait event on the additional surfaces tended to be similar to those recorded on asphalt, indicating that the novel method agreed equally well with the reference method on the additional surfaces as it did on asphalt, for which the reference method was validated. The excellent agreement of the novel methods with the reference on all surfaces is again reflected in the very high values of sensitivity and PPV (≥97%), indicating that the novel methods rarely identified false negatives or false positives, respectively.

Small differences between surfaces were observed for the mean errors and sd of the errors, but none of these differences were of noteworthy magnitude, and they were only statistically significant for the forelimbs at trot. Therefore, it is concluded that the novel methods showed equally good agreement with the reference method on all surfaces when used to calculate stance durations.

In the case of hindlimbs at trot (Fig 3.5D), the Bland-Altman plot appears to show that the method tended to underestimate the stance duration for mean stance durations of over 300ms. However, data points above 300ms falling below the LLoA (10 points) are very few compared to the points which fell within the LoA. Conversely, the Bland-Altman plot for the hindlimbs at trot suggest that the method tended more frequently to overestimate the stance duration for mean stance durations below 300ms. However, the points here falling above the ULoA, compared to those falling within the LoA, are again only a small minority. These two observations could warrant further testing to determine whether there is a trend between the stance phase duration and tendency of the method to under- or overestimate the stance duration.

No significant effects due to the individual horse were seen and the Bland-Altman plots suggest that, apart from the details of hindlimb trot discussed above, the errors incurred were consistent for different durations of stance. This indicates that the method can be used for different horses and under different surface conditions.

3.4.3 Limitations and future work

The most noteworthy limitations to this research relate to the use of the hoof-based method[196] for registering reference timings of gait events as a ground-truth. This method has only been validated for data collected in the lab, on one hard surface, with results compared to a force plate. However, a previous study which used a hoof-mounted accelerometer[174], found that gait events could be manually selected from acceleration signals recorded on both hard and soft surfaces. Furthermore, in the present study, visual inspection of Acc_R and ω_R recorded from the hooves on the softer surfaces revealed that they were comparable to those recorded on asphalt, with similar peaks prominent (see 3.6 Appendix for example signals). Therefore, it was assumed that the hoof-based method held for all surfaces. Although a varied group was selected in the interests of yielding widely applicable results, the cohort size, while larger than in many similar studies, was still somewhat limited and it would be beneficial to validate the methods for more individuals. In the future, use of pastern-mounted sensors should also be investigated for other gaits, which can be important in lameness workups[29], and for use on data collected during curvilinear walk and trot. Despite exercise in circles forming a key component of both training and lameness workups[29], literature has been very limited in terms validating IMU based gait event detection methods for the condition of circling and the publication which does exist addresses only trot[265]. In a study by Starke and Clayton[188], authors described and extensively validated methods which used a dorsal hoof-mounted reflective marker and OMC to detect gait events for the fore and hindlimbs at walk and trot in straight lines and on a circle. Gait event detection using IMUs would benefit from a similar study, with validation on circles included for both walk and trot.

3.5 Conclusion

In conclusion, this study has developed several methods of gait event detection which make use of different IMU attachment locations and signal processing methods. These tools were validated by comparing the timing of detected gait events to those detected using hoof-based methods which, themselves, had been previously validated on a hard surface against a force plate and proven to be a suitable alternative for the purpose. The performance of the novel methods was consistent across the entire, varied cohort with pastern-based methods proving superior to the current state-of-the-art cannon-based options. Events detected from the pastern-mounted IMUs using a method of peak detection applied to the resultants of angular velocity (for forelimbs at trot) and acceleration (for all other limb/gait combinations) were used to calculate stance durations with a high level of accuracy and precision on asphalt. Furthermore, gait events detected on grass and sand by these methods were used to calculate stance durations which proved to have good agreement with those calculated using the hoof-based methods on these additional surfaces, maintaining consistently low errors. The LoA suggest that methods of forelimb hoof-on detection may be accurate enough to detect alterations of stride duration seen in cases of moderate lameness but that they are not sufficiently accurate to use for investigating such changes due to mild lameness.

Thus, the developed methods can be used as an alternative to hoof-mounted methods, when the latter is not convenient, to detect gait events under a range of surface conditions and for a varied cohort of subjects. This can certainly be extremely beneficial for future studies undertaken in a variety of field conditions.

3.6 Appendix – Example Signals

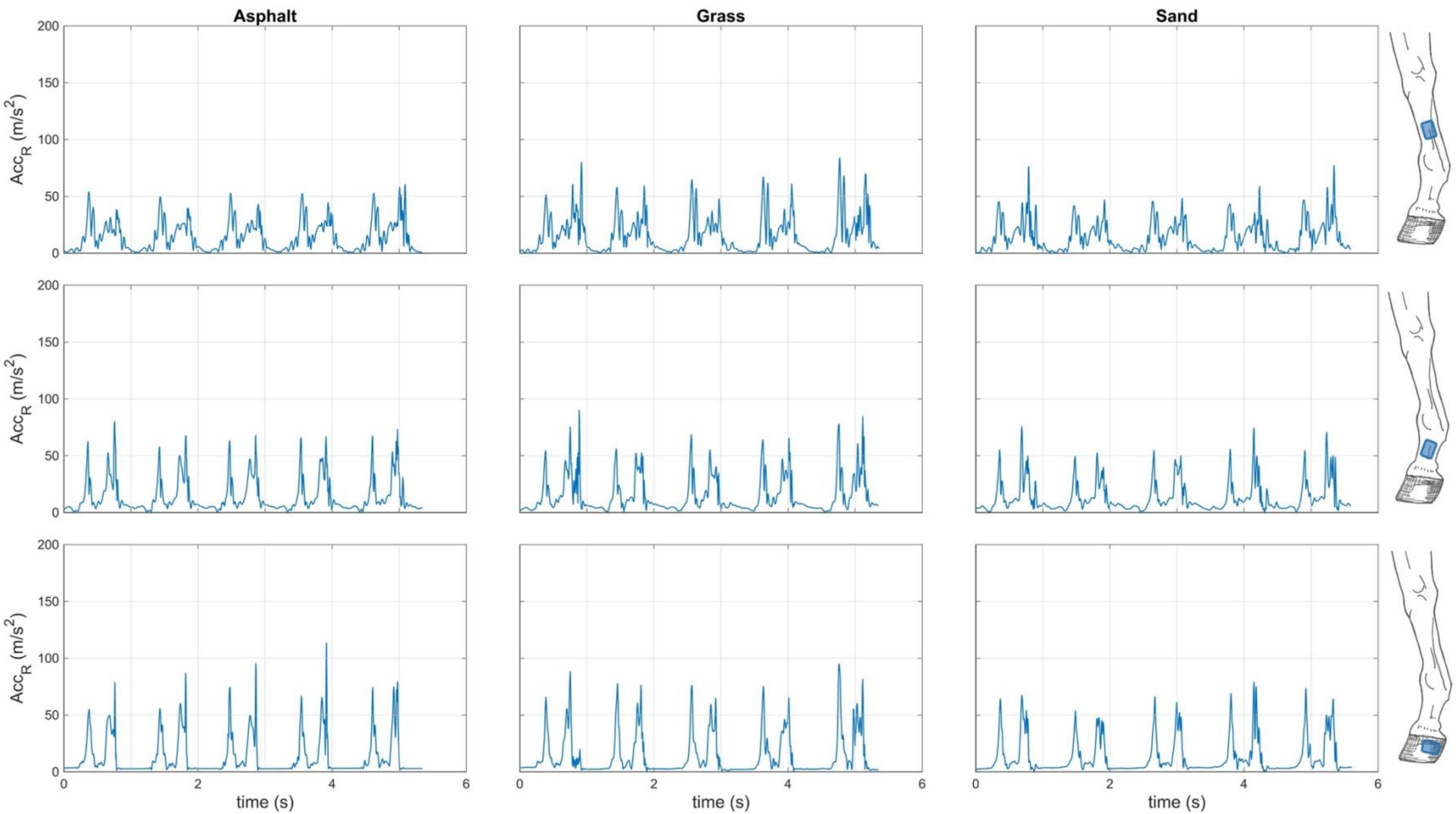


*Figure 3.6 examples of **resultant accelerations** (Acc_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **forelimb at walk** on asphalt (left), grass (middle) and sand (right).*

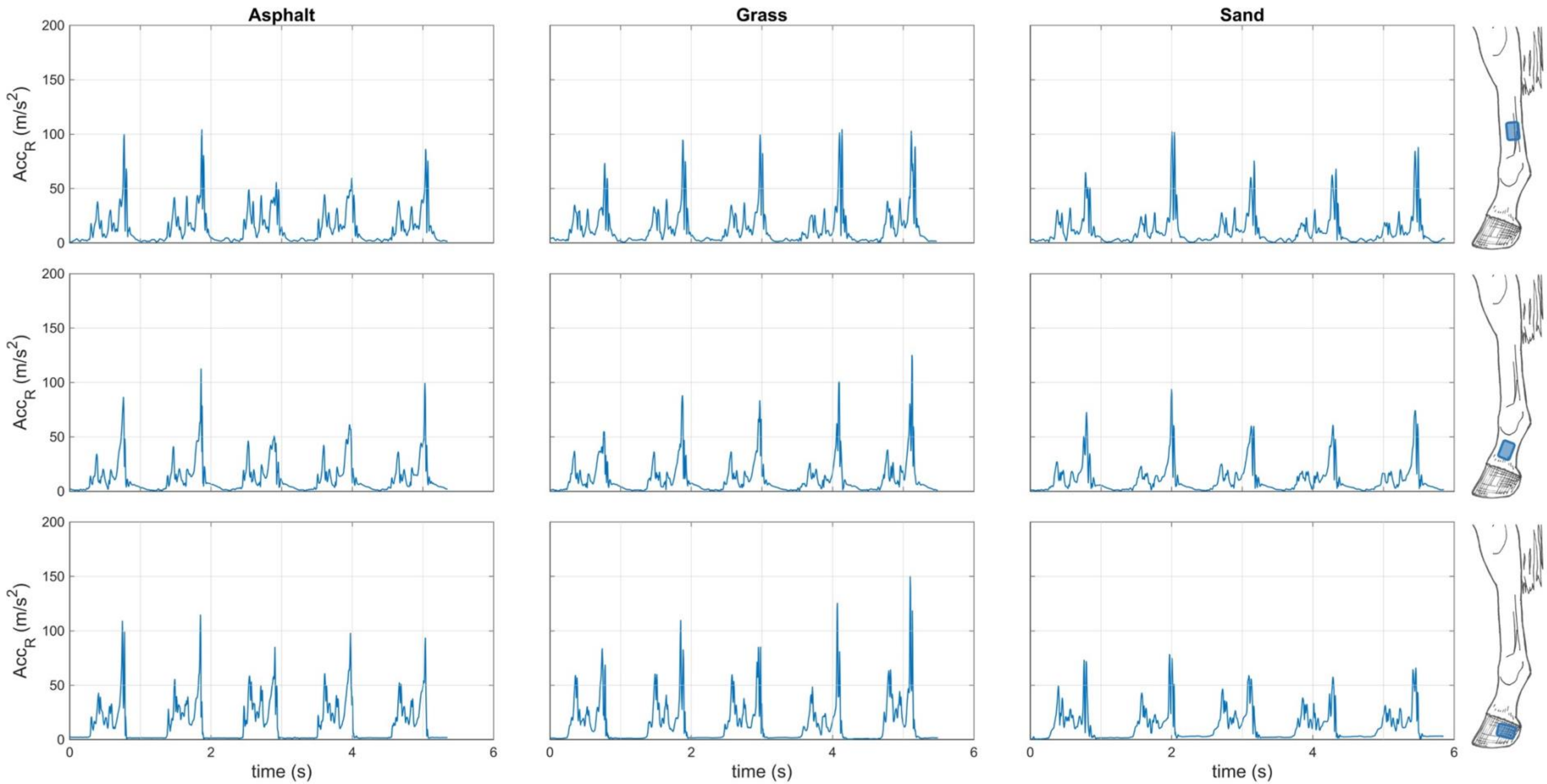


*Figure 3.7 examples of **resultant accelerations** (Acc$_R$) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **hindlimb at walk** on asphalt (left), grass (middle) and sand (right).*

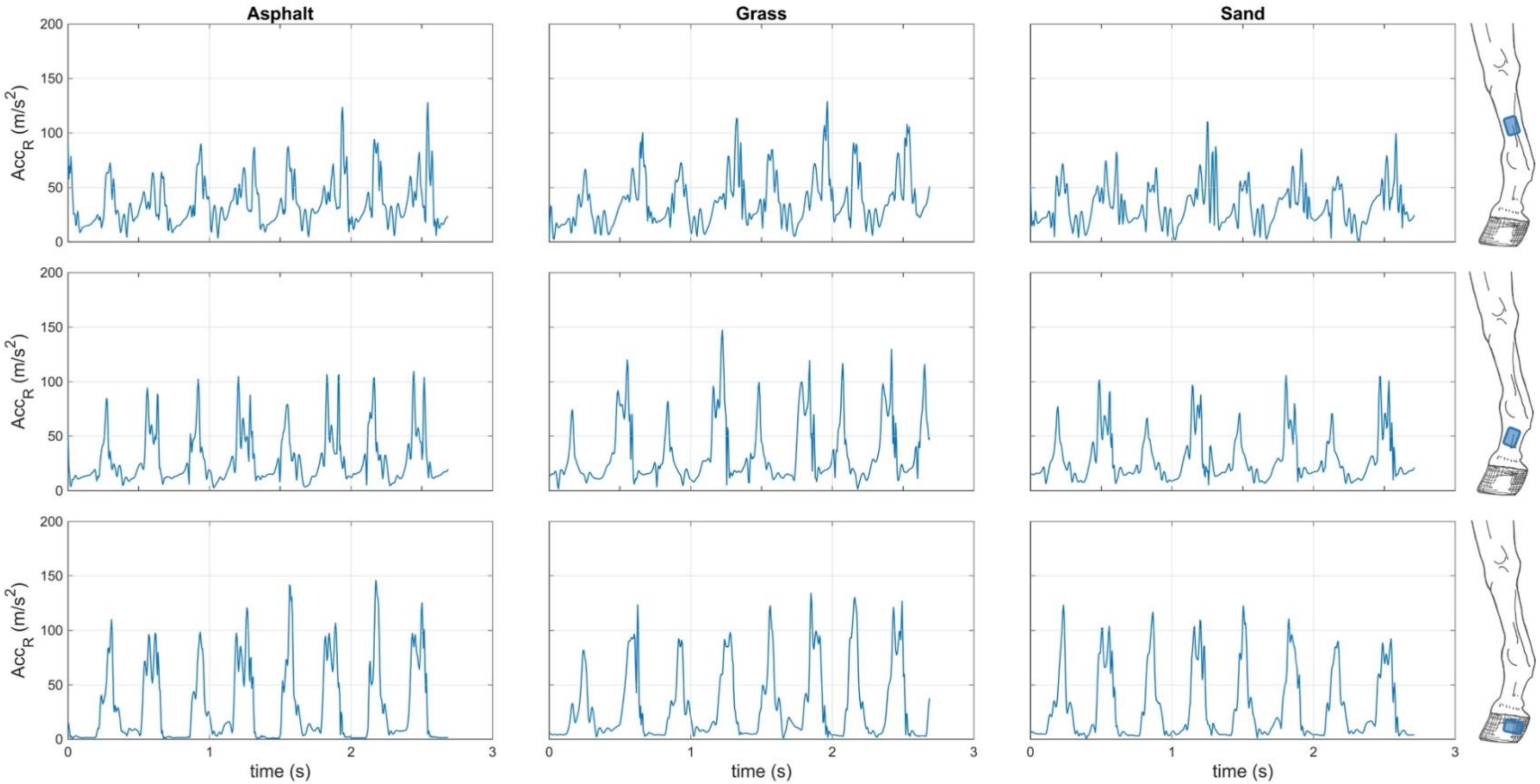


*Figure 3.8 examples of **resultant accelerations** (Acc_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **forelimb at trot** on asphalt (left), grass (middle) and sand (right).*

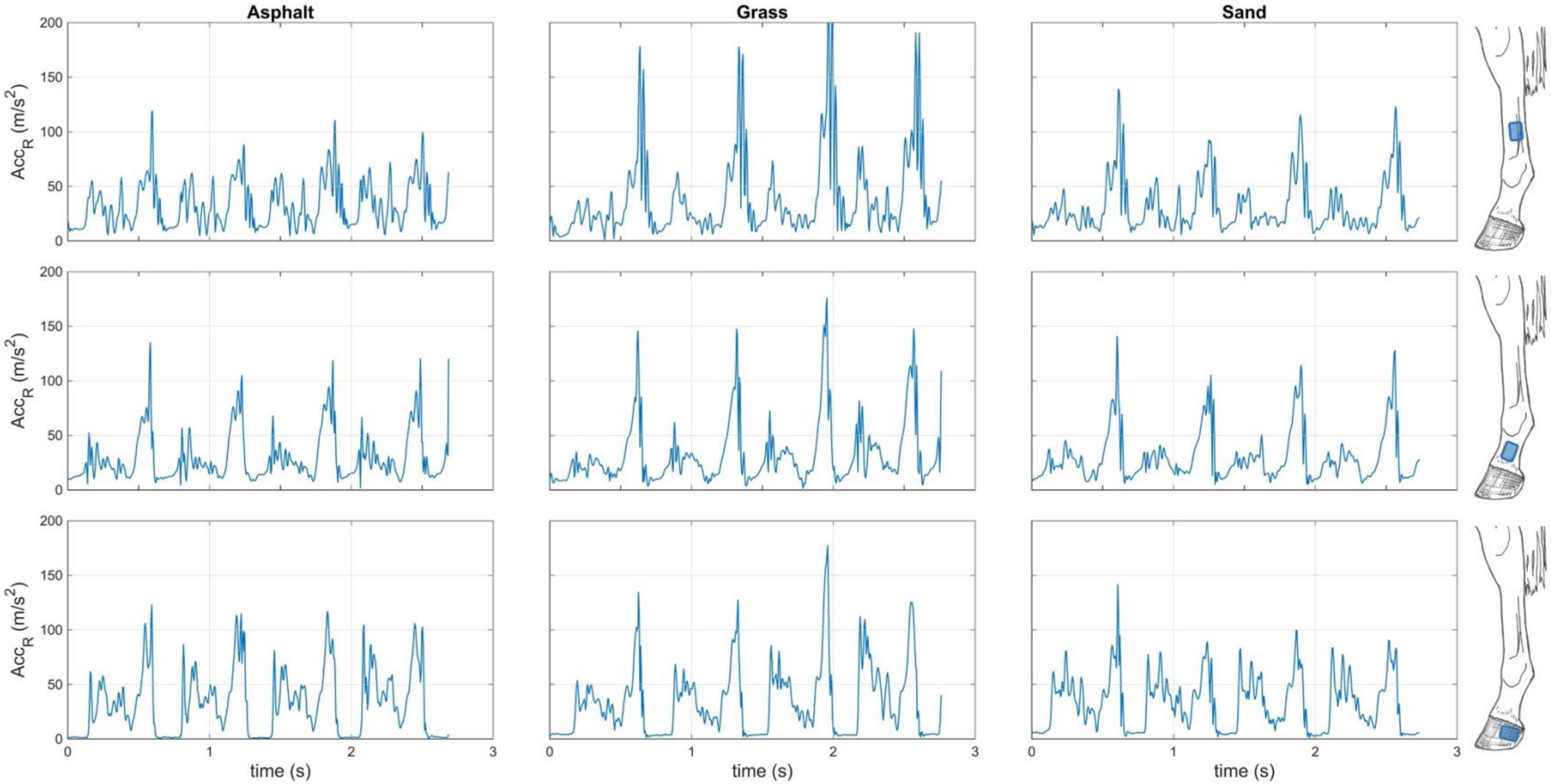


*Figure 3.9 examples of **resultant accelerations** (Acc_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **hindlimb at trot** on asphalt (left), grass (middle) and sand (right).*

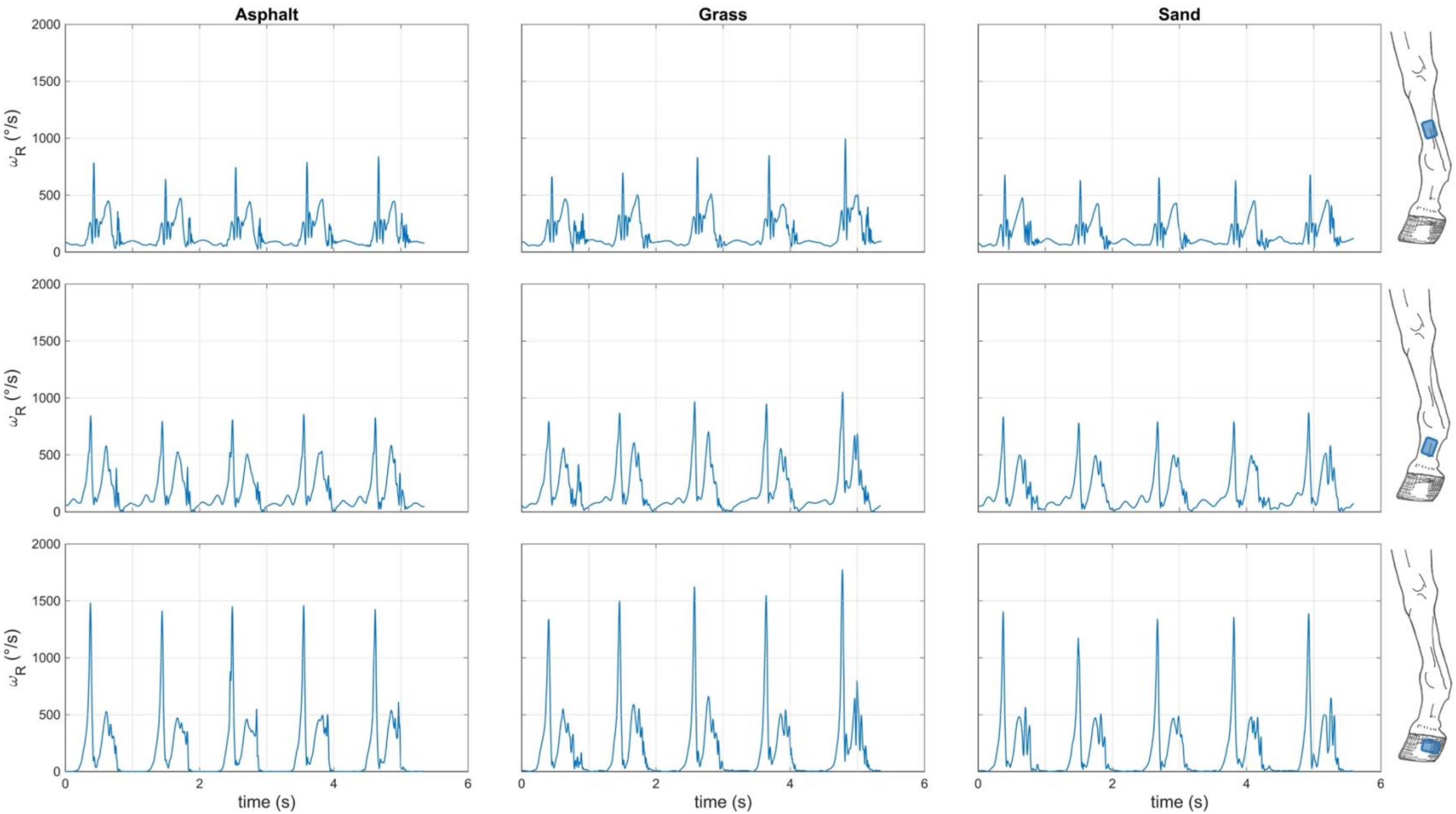


*Figure 3.10 examples of **resultant angular velocity** (ω_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **forelimb at walk** on asphalt (left), grass (middle) and sand (right).*

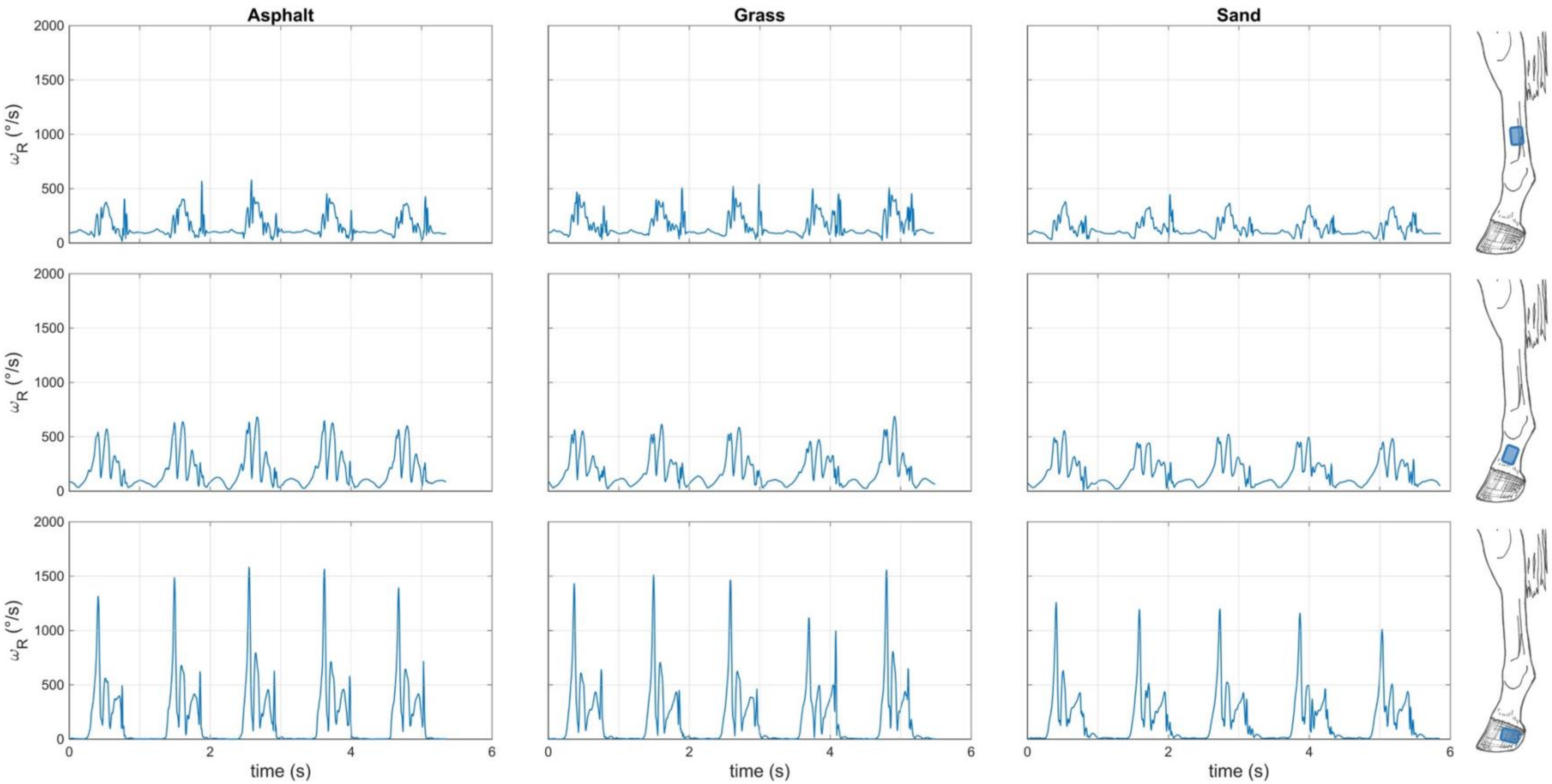


*Figure 3.11 examples of **resultant angular velocity** (ω_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **hindlimb at walk** on asphalt (left), grass (middle) and sand (right).*

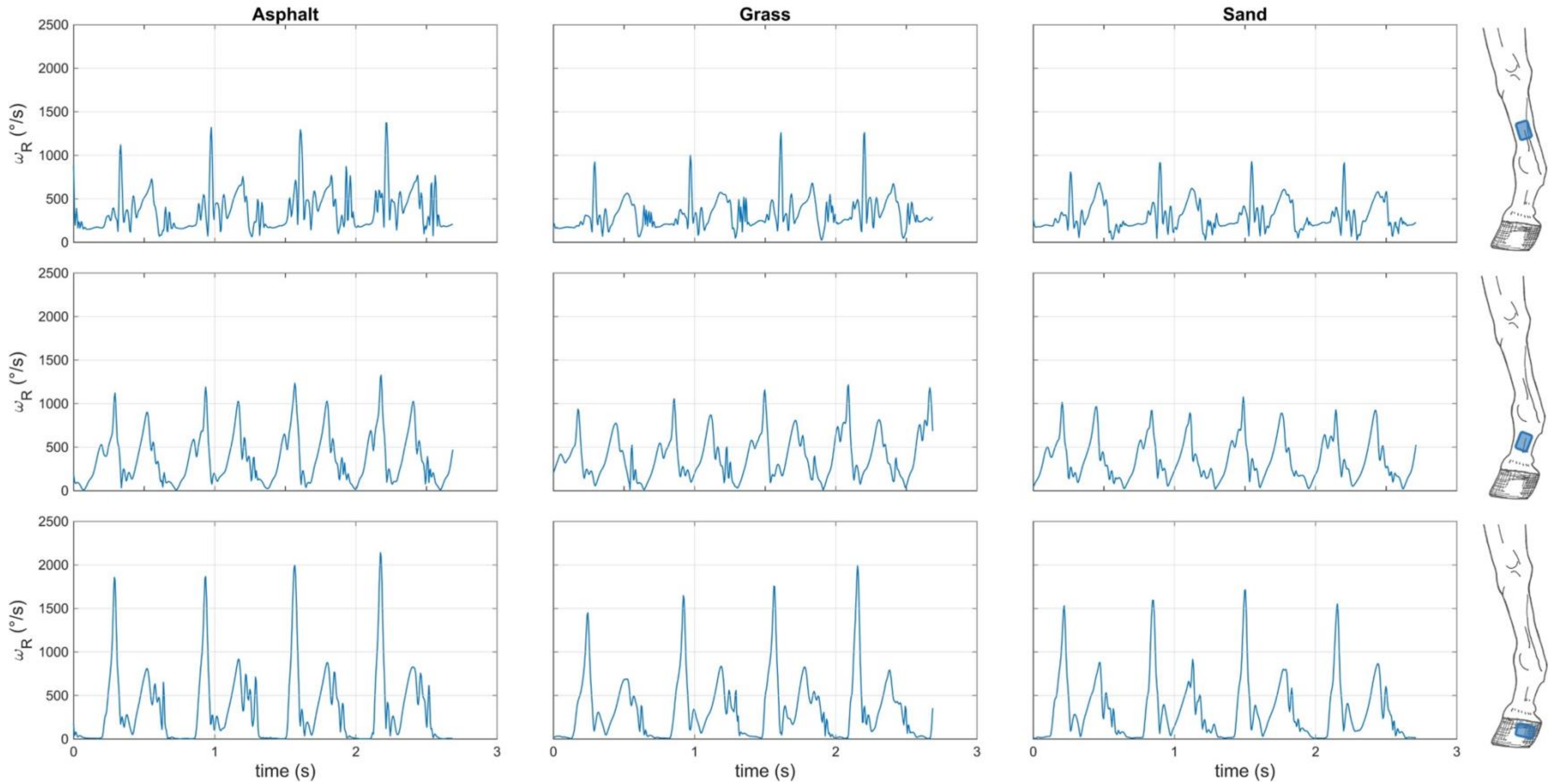


*Figure 3.12 examples of **resultant angular velocity** (ω_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **forelimb at trot** on asphalt (left), grass (middle) and sand (right).*

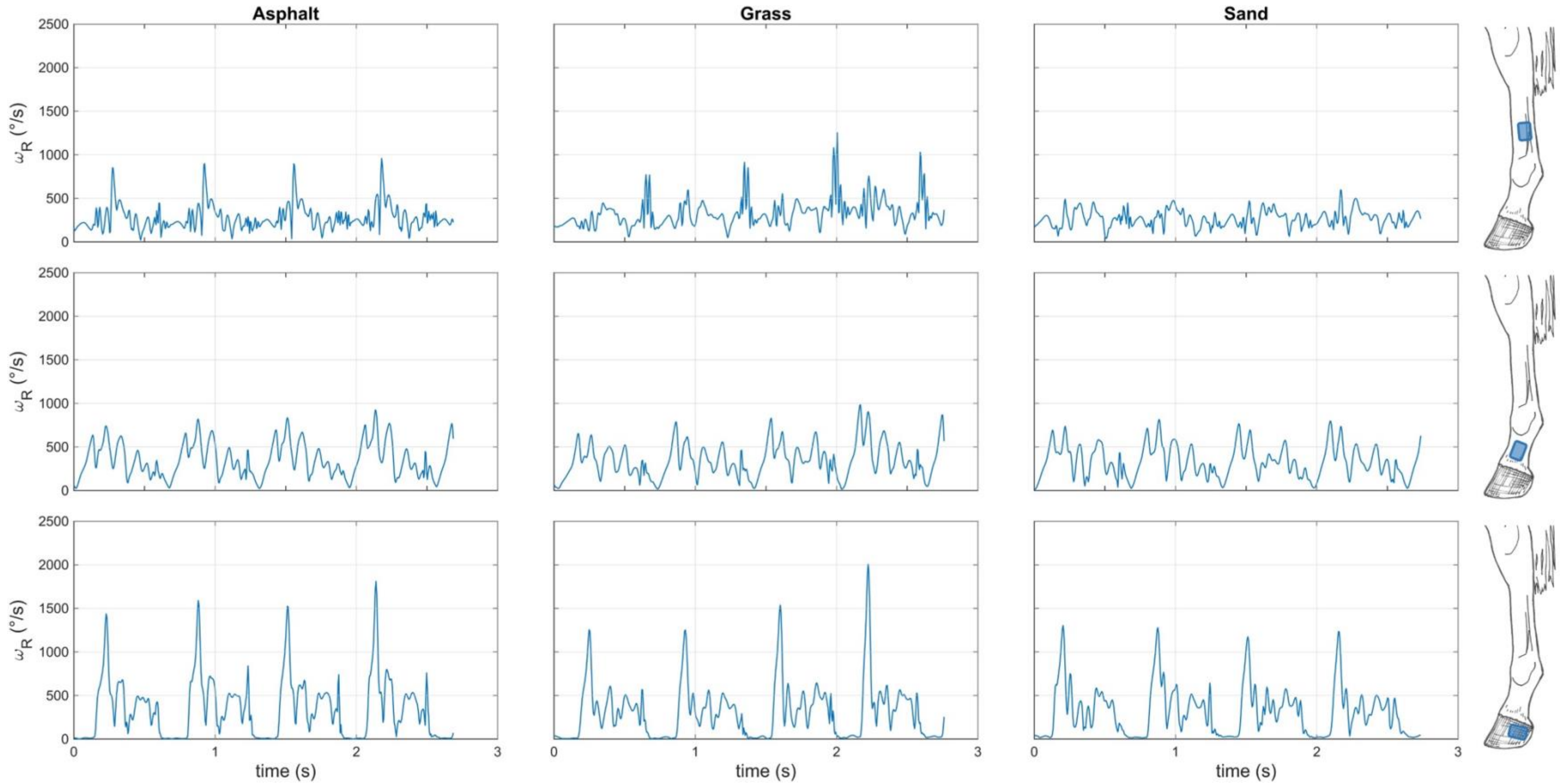


*Figure 3.13 examples of **resultant angular velocity** (ω_R) recorded concurrently from cannon (top), pastern (middle) and hoof (bottom) of **hindlimb at trot** on asphalt (left), grass (middle) and sand (right).*

Chapter 4 Effect of Unilateral Dominant Lameness on Breakover Duration

4.1 Introduction

The motion of each limb during a stride cycle can be split into the stance and swing phases. The latter can further be broken down into several phases during which the limb is loaded and unloaded. Loading begins with the primary impact, in which the hoof and pastern segments are rapidly decelerated first in the vertical and then the horizontal direction[266]. Following this, during the secondary impact, the proximal limb descends and collides with the distal limb segments before the body mass is added to the loading. This secondary impact is characterised by lower decelerations and higher forces than the initial impact[266], and it begins the support phase, in which the fetlock joint is extended in accordance with the stretch and recoil cycle of the superficial digital flexor tendon and the suspensory ligaments[267]. The point of force application (PoF) is the point at which the GRF (Fig 4.1, GRF, red upward arrow) can be assumed to act[268]. During the support phase, the GRF acts to extend the distal interphalangeal (DIP) joint[269]. As the PoF is not positioned directly beneath the centre of rotation (Fig 4.1, point C) of the structures (instead it is positioned more cranially, towards the toe of the hoof,) the action of the GRF through the PoF creates a torque which acts as the extending moment (Fig 4.1, M_{EXT}) of the DIP joint[269]. This is opposed by a flexing moment (Fig 4.1, M_{FLX}) generated by tension in the deep digital flexor tendon (DDFT) as it runs over the navicular bone. At the end of the support phase, the PoF moves across the solar surface of the hoof towards the toe as the flexing moment created by tension in the DDFT and navicular structures on the palmar (forelimbs) or planter (hindlimbs) side of the coffin joint exceeds that created by the GRF on the dorsal side and the heel is gradually unloaded. When the PoF reaches the point of breakover[270,271] (the most cranial point of the solar surface to contact the ground; Fig 4.1, PoB) and can go no further, the extending moment reduces in line with the reducing GRF and the flexing moment enables flexion of the DIP joint which allows heel lift-off (onset of breakover) and the subsequent articulation of the heel around the toe, which acts as a fulcrum[272], during the breakover phase[39,55,273,274].

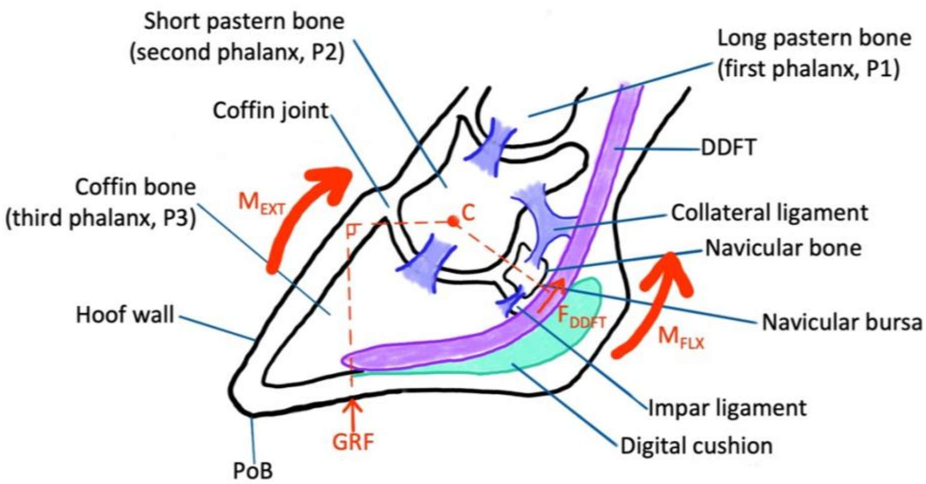


Figure 4.1 illustration of the mechanisms of breakover. C marks the centre of rotation. The GRF (red arrow) acts through the PoF (which moves dorsally during stance) creating a moment arm which results in the extending moment (M_{EXT}). This is countered by a flexing moment (M_{FLX}) which is the result of tension in the DDFT and impar ligament. The PoF moves cranially towards the toe until it reaches the PoB when M_{FLX} exceeds M_{EXT}, the heel is lifted and breakover commences.

In the literature, there appears to be some disagreement as to how long breakover duration lasts as a percentage of the stance duration. At walk, one group investigated French Trotters walking in a straight-line on asphalt, finding that the breakover duration of the forelimbs lasted for around 10% of the stance duration[17,275]. This is in slight contrast to the findings of Hodson et al. and Tijssen et al. who reported that the breakover duration at lasted 14.1%[276] and 17(5)%[197], respectively, for the forelimbs at walk and 15.4%[277] and 13(4)%[197] for the hindlimbs. At trot, some have reported the breakover durations to last as long as 25% of the stance at a medium speed[272], while others recorded durations of nearer 20% for the forelimbs on a treadmill[278] and for the fore and hindlimbs overground[197].

Most previous studies of breakover duration focussed on the effects of different farriery methods[273,274,279] and speed and surface conditions[191]. 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.

It is well understood that the mechanisms of lameness exist to alleviate pain in affected limbs by redistributing forces onto the other limbs[39]. Unilateral lameness causes a significant reduction in vertical GRFs in the lame limb compared to the contralateral[36,65,66]. In horses measured on an instrumented treadmill at trot, both fore[201] and hindlimb[27] lameness was found to: cause a total reduction in vertical impulse per stride; decrease impulse during the stance of the lame diagonal; shift the impulse to the hindlimb of the affected diagonal pair in forelimb lameness and to the forelimb of the affected pair in hindlimb lameness; and reduce the rate of loading and peak vertical force by prolonging the stance duration.

Clayton et al.[41] suggested a causal link between the mechanism of vertical GRF redistribution due to lameness and breakover. They reported that, in lame horses trotting over a force plate, centre of pressure in the lame limb began to move rapidly forward at a relatively early stage of the stance duration resulting in a prolonged breakover duration, compared to during that of the contralateral sound limb. They suggested that the lower GRFs experienced by a lame limb would result in a smaller GRF and DIP joint moment arm[280] and, thus, that this would be overcome by the tensile forces of the DDFT earlier in the stance phase, resulting in an earlier heel-off and, thus, a prolonged breakover duration.

Beyond this early suggestion of a link between lameness and breakover duration, only a handful of studies have reported on the relationship. Small differences have been found at walk between the breakover durations of an affected limb at baseline readings and after induction of unilateral forelimb lameness[205]. At trot, researchers found small reductions in breakover duration in the affected limb from baseline readings to Grade 2 lameness (-2ms) and after perineural anaesthesia (-3ms)[208]. No significant differences were reported between the breakover durations of the treated and contralateral forelimb, suggesting that lameness did not affect the left/right symmetry of breakover durations. The kinematics of the hindlimbs were not investigated. Further 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[43] chronic sesamoiditis of the fetlock joint[42] or fracture of the third carpal bone[207]. To the best of the author's knowledge, there have been no previous investigations into 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 hypothesised that lameness would influence breakover duration, inducing a longer breakover in the most severely affected limb compared to the contralateral limb.

4.2 Materials and Methods

4.2.1 Horses

Sixteen horses (eight geldings; eight mares) of various breeds and uses, with mean(sd) height 164(9) cm and age 13(5) years were included (Table 4.1). Five were presented sound by the owners (Horses 1-5) while four were suffering from acute lameness and seven had histories of chronic lameness. Horses were not assessed by a clinician specifically for the purpose of the study; thus, each was assigned to the sound or lame group based on the veterinary history provided by their owner and the grade of lameness of each horse was not obtained. For the lame group, lameness predominated in one forelimb for three horses (Horses 6-8) and one hindlimb for seven (Horse 9-15), while one horse suffered lameness predominating in both one fore and the diagonal hindlimb (Horse 16). For each lame horse, the owner gave an account of the clinical history, including diagnoses the horse had received and whether lameness was more prevalent in the left or right, and fore or hindlimbs (referred to as *clinical observations* in the following sections). The lameness severities studied ranged from one horse which was still competing at top level eventing while receiving ongoing steroidal treatment for osteoarthritis of the fetlock joint, to three horses which were out of work or permanently retired due to lameness. For additional details of the cohort, see section 4.5 Appendix

Table 4.1 details of the cohort.

Horse ID	Age (years)	Height (cm)	Lameness state
1-5	13(6)	162(9)	Sound
6-8	16(4)	163(14)	Three forelimb lame
9-15	14(5)	164(5)	Seven hindlimb lame
16	14	168	One LF and RH lame
mean(sd)	13(5)	164(9)	-

4.2.2 Data collection and measuring protocol

IMUs (Shimmer3 IMU) containing tri-axial accelerometers (range ±200g, where g is acceleration due to gravity, 9.81m/s^2) and gyroscopes (range ±2000°/s) were set to a sampling rate of 200Hz and firmly attached to the lateral aspect of the four hooves using sticky-back hook and loop fastenings. Horses were walked and trotted in-hand, at self-selected speeds, along a flat, hard track of 35m, with the central 25m being used for the data processing stages. Three passes were recorded per horse per gait, including only trials where no significant disturbances occurred (such as the horse breaking out of the desired gait). The methods were reviewed and approved by The University of Sheffield, Ethics Department (Reference Number 033398), and owners gave informed consent for their animal's involvement.

4.2.3 Data analysis

4.2.3.1 Calculating temporal parameters

The hoof-on, -off and onset of breakover (recall Chapter 1, Fig 1.4) were detected from the angular velocities (Fig 4.2) using previously proposed and validated methods[196,197,281]. Briefly, the resultant of angular velocity (ω_R) was calculated and filtered using a second order Butterworth filter with cut off frequency 40Hz. From this, instances of hoof-on (h_{on}) and -off (h_{off}) were identified by peaks in the signal (as per Chapter 3). Using these, the midstance of each stride was found as the halfway point between the hoof-on and -off. A threshold (x_{th}, Eq. 4.1) was determined for each stride and the point where the signal first exceeded and subsequently remained above this threshold was taken as the onset of breakover (b_{ov}). This threshold was modified from that which was suggested in the original paper[197] (which appeared to give inconsistent estimations of b_{ov}- sometimes detecting points too close to either midstance or hoof-off) and was calculated as 5% of the mean of the signal ($\bar{x}$) between the midstance and subsequent hoof-off of that stride. For every stride included in analyses, the signals were visually inspected to ensure sensible estimations of b_{ov}.

$$x_{th} = \bar{x} \cdot 0.05 \qquad (4.1)$$

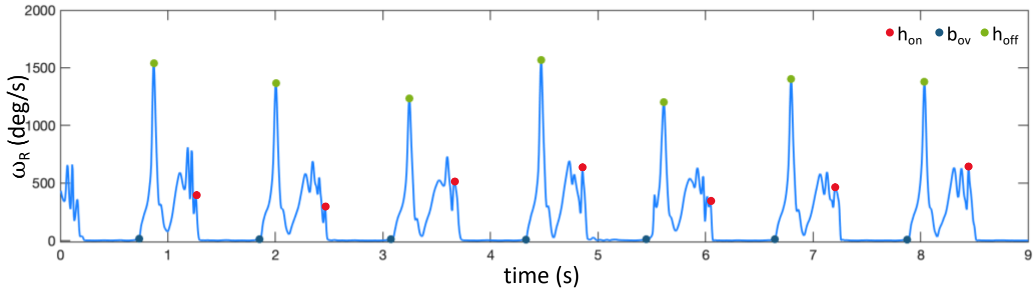


Figure 4.2 illustration of hoof-on (h_{on}, red dots), -off (h_{off}, green dots) and onset of breakover (b_{ov}, indigo dots) detection from resultant of angular velocity (ω_R); seven consecutive walk stride cycles for one limb are presented.

Stance durations (t_{stance}, ms) were calculated as the time from hoof-on to the subsequent hoof-off of the same limb (as per Chapter 1, Eq 1.2) and breakover durations (T_{BO}, ms) were calculated as the time from the onset of breakover to hoof-off, for each limb (Chapter 1, Eq 1.3). To investigate the results of stance and breakover duration, the data were split into sound, lame and opposite groups of limb pairs, which were defined as per Table 4.2.

These groups did not include the one horse presenting with lameness predominating in one fore and diagonal hindlimb (Horse 16). The between-limb differences (those between the sound and contralateral limb of a sound limb pair, or lame and contralateral limb of a lame pair) were tested for significance using statistical methods. The breakover durations 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 the sound and contralateral limbs of these pairs were tested for significance using a Wilcoxon Signed Rank test. All other datasets proved to be normal, and significance of between-limb differences were tested using paired Student's t-tests.

Table 4.2 definition of the groups into which limb pairs were sorted for the purpose of analysis. The name of the group, definition and examples of which limbs would be assigned to each group are provided.

Group	Description	Example
Sound	Both contralateral limb pairs (fore and hind) of each sound horse, where limbs were 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* (limb where lameness predominated) and *contralateral* limbs of lame horses.	For a LF lame horse, this would be the LF (lame) and RF (contralateral) limbs. For a RH lame horse, this would be the RH (lame) and LH (contralateral) limbs.
Opposite	The *ipsilateral* and *diagonal* (with respect to the lame limb) limbs of lame horses.	For a LF lame horse, this would be the LH (ipsilateral) and RH (diagonal) limbs. For a RH lame horse, this would be the RF (ipsilateral) and LF (diagonal) limbs.

4.2.3.2 Comparing contralateral breakover durations

For every walk stride, the mean difference ($\overline{\Delta \mathrm{T_{BO}}}$, ms) between the breakover durations of the right ($\mathrm{T_{BO_R}}$) and left ($\mathrm{T_{BO_L}}$) limbs of the contralateral limb pair was calculated (Eq 4.2).

$$\overline{\Delta \mathrm{T_{BO}}} = \frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{T_{BO_R}} - \mathrm{T_{BO_L}}\right)_i \qquad (4.2)$$

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

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

Then, statistical methods were used to test the null hypothesis that, for each individual horse, the mean breakover duration of the left and right limb of each contralateral limb pair was not significantly different. Shapiro-Wilks test for normality and visual inspection of the QQ-plots indicated that the datasets were normally distributed. Therefore, for each horse, paired Student's t-tests were used to detect statistically significant differences in breakover durations, 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 of horses. All data and statistical analyses were carried out using custom scripts written in Matlab (version 2021R).

4.3 Results and Discussion

A total of 700 walk and 543 trot strides were analysed, with an average of 41(10) and 34(9) strides per horse, respectively.

4.3.1 Effect of lameness on temporal stride parameters

Fig 4.3 presents the results of the stance and breakover durations of the sound (sound and contralateral limbs) and lame (lame and contralateral limbs) pairs at walk and trot. No differences were observed between the mean stance durations of sound and contralateral limbs of sound limb pairs at walk (p=0.4, effect size=-0.197) or trot (p=0.6, effect size=0.07), in agreement with literature[51,205]. Similarly, no differences were observed in lame limb pairs between the stance durations of the lame and contralateral limbs at walk (p=0.96, effect size=0.009) or trot (p=0.94, effect size=0.007), indicating that the prevalence of lameness in one limb of the contralateral pair did not affect the stance duration symmetry at walk. Moreover, the mean stance durations of the lame and sound groups were comparable to each other at walk (801(45)ms and 795(29)ms, respectively) and trot (293(18)ms and 318(32), respectively). Thus, results suggest that lameness does not affect the symmetry of the stance durations at walk or trot, in agreement with literature[51].

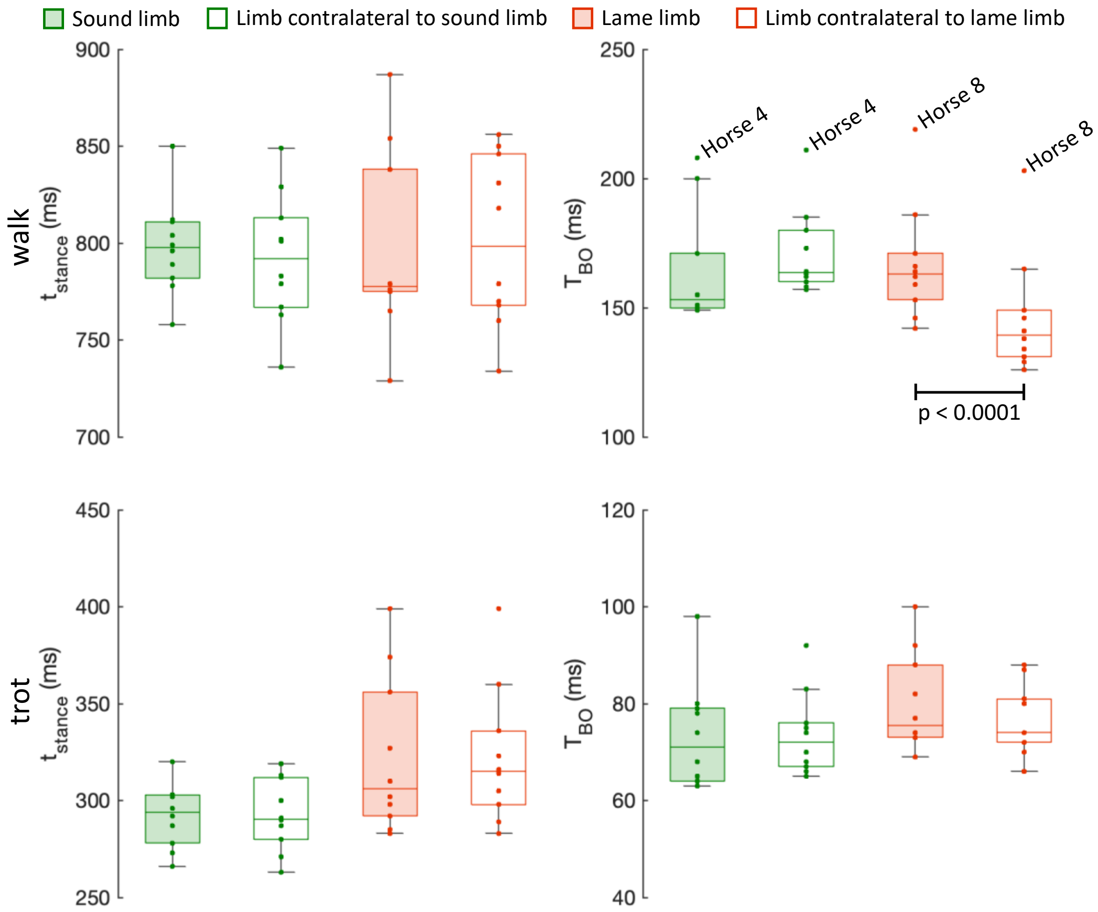


Figure 4.3 stance (t_{stance}) and breakover durations (T_{BO}), in ms, for walk (top) and trot (bottom) calculated for limb pairs of sound and lame horses. Results of sound and corresponding contralateral limbs of sound limb pairs (solid green and empty green boxes), and of lame and corresponding contralateral limbs of lame limb pairs (solid red and empty red boxes) are given. Individual data points from sound and lame horses are given as green (•) and red (•) dots, respectively. Where differences were statistically significant, p-values are shown and outliers of interest are labelled with the horse number.

For sound limb pairs, the recorded breakover durations were slightly longer for walk (21(2)% of stance duration) than those reported in the literature[17,275–277]. There may be several possible explanations for this. Firstly, the morphology of the cohort may have had an influence with the present study comprising several different breeds of horse with mean(sd) height 163(14)cm. In comparison, groups studied in the literature were made up of French Trotters of height 158(4)cm, recording walking breakover durations of 10%[17,275], and different breeds of heights 143-156cm, recording values of 15%[276]. Another explanation for the differences could lie in the velocity. In the cited studies, the average velocities were 1.28m/s[17,275] and 1.49m/s[276], respectively. In the present study, horse velocity was not recorded but it could be suggested that velocity may have contributed to the disagreement with the literature, as breakover duration is known to be heavily dependent on speed[197,282].

The trot breakover durations of the sound group (25(2)%) were towards the higher end of values reported in the literature, (ranging from around 20%[197,278,283] to 25%[272]).

The disagreements in breakover duration, both in the literature and here, warrant further investigation. Breakover durations appear to be dependent on the equipment and methods used to detect the gait events and calculate the parameter; in the literature, various means have been used. Hodson et al. used a combination of force plate recordings and visual inspection of OMC videos to determine instances of hoof-on, -off and onset of breakover[276,277]. Meanwhile Chateau et al.[17,275,278]. used a system of kinematic markers, surgically attached to the bony structures beneath, with miniature ultrasound microphones attached. The position of these relative to a fixed system of ultrasound transmitters was derived using triangulation from the time delay between ultrasound pulses. When Tijssen et al.[196,197] developed the methods to detect gait events and onset of breakover which were used in the present study, they investigated the use of accelerometers, gyroscopes, force plates and OMC. The methods were applied to data recorded concurrently, from the same strides. Despite this, different breakover durations were reported not only for the different limbs (fore and hind) and gaits (walk and trot), but also for the different types of signals processed. For instance, for the forelimbs at walk, the mean breakover durations reported ranged from 9% of the stance duration for values recorded using OMC, to 22% for those using angular velocities. Nonetheless, the standard deviations were similar for each method, ranging from 4% for the angular velocities and OMC, to 6% for the acceleration-based method. These results suggest breakover durations recorded using different methods might not be suitable for comparison but that, if the same methods are applied consistently, any can be used with equal reliability for comparison of breakover durations within a study (as is the case here) because the standard deviations were similar.

Breakover durations have previously been found to be gait dependent[17,275,278,279], not only because the kinematics of walk and trot differ significantly but also because the characteristics of breakover are heavily influenced by speed and, hence, gait[197,282] becoming shorter with increasing velocity. The mean(sd) breakover durations as a percentage of stance duration of the sound group was 21(2)% for walk and 25(3)% for trot (where a paired Student's t-test revealed p<0.0001). This agreed with previous literature, where the relative breakover duration of the forelimb increased from 14.5% at walk to 19% at trot[283] in one study, and from 15% to 21% in another[197].

At walk, the breakover durations of the sound forelimbs (182(21)ms) were significantly (p=0.0018, paired Student's t-test) longer than those of the sound hindlimbs (158(6)ms). This agrees with previous literature where forelimb breakovers at walk were found to be 114ms[276] and 141(16)ms[283], compared to 106ms[277] and 118(24)ms[283], respectively. This could be explained by the natural difference in conformation between the fore and hindlimb hooves[284,285]; indeed, in a study on the effect of toe angle on hoof growth[286], it was reported that the toe angle of the forelimbs tended back to 45° between farriery cycles, while that of the hindlimbs tended towards 52-53°.This would explain the longer breakover durations of the forelimbs as there is a longer moment arm created by the smaller hoof angle and longer toe length[269]. It could be hypothesised that the longer breakover durations of the forelimbs, compared to the hind, results in higher tensile stresses being experienced in the distal forelimbs. This, in turn, may contribute to the higher incidence of concussive injuries seen in forelimbs compared to hind[39]. At trot, no significant differences were seen between the breakover durations of the fore (76(11)ms) and hindlimbs (70(8)ms) which also agreed with literature[197,283].

For sound contralateral limb pairs, the breakover durations of the left and right limbs showed negligible differences at walk (p=0.07, effect size=-0.3) and trot (p=-0.9, effect size=-0.02), reflecting the symmetrical nature of healthy walk. This symmetry in the breakover duration has previously been reported for trot[208,282]. One publication[205] did report statistically significant differences between breakover duration of sound contralateral forelimbs at walk; however, in that case the magnitude of the difference (4ms) was actually negligible. Thus, it can be concluded that there should be left/right symmetry of breakover durations in fore and hind contralateral limb pairs at both walk and trot, in a sound horse.

At trot, the symmetry of breakover duration was maintained for the lame group, with the lame and contralateral limbs having mean breakover durations of 80(10)ms and 76(7)ms, respectively (p=0.4, effect size=0.17). In contrast to this finding, in a series of forelimb lameness case studies the breakover duration of the affected limb at trot was found to be significantly longer than that of the contralateral. However, in two of these cases the lameness was so severe that the horse was reluctant to weight-bear on the affected limb at rest[42,43], and the differences in breakover durations of contralateral limbs were 38ms and 29ms, respectively. In a further case, when the horse was only grade 2 lame, the mean difference was only 6ms[207]. In agreement with the current study, symmetry of breakover duration has previously been reported to be maintained with the induction of grade 1, 2 and 3 unilateral forelimb lameness[208] Hence, it may be hypothesised that symmetry of breakover duration at trot is impaired only in cases of very severe lameness.

In contrast to trot, at walk there was an asymmetry in the breakover duration of lame limb pairs, with the mean breakover duration of the lame limb (167(22)ms) being comparable to those of sound limb pairs (168(19)ms), with only a 2ms difference, and the breakover duration of limbs contralateral to lame being 14% shorter (146(23)ms, p<0.0001, effect size=0.9). These results support the hypothesis that lameness induces a longer breakover duration in the lame limb and shorter breakover in the contralateral limb. A prolonged breakover duration has previously been associated with a longer toe length and thus an increase in the risk of developing specific pathologies as a result of increased tensile stresses in the DDFT and impar ligament and related increased compression of the navicular bursa and navicular bone[272], such as navicular disease[287] or tendon injury[197,272,274]. However, the diverse range of lameness causes represented in this cohort (see 4.5 Appendix) suggest that, not only can prolonged breakover duration predispose an animal to injury or disease, but it may also develop as a result of a wide range of underlying pathologies. These results support the suggestion by Clayton et al.[280] 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, this author suggests that breakdowns in the left/right symmetry of breakover duration develop as a coping strategy for accommodating lameness.

The result is perhaps surprising as it has long been believed that persistent lameness leads to increased hoof angles and a more upright dorsal hoof wall[288] which, it would seem, would tend to shorten the breakover duration. However, only insignificantly (p=0.4) larger hoof angles have sometimes been reported in lame limbs (53(3) °) compared to non-lame (52(4)°)[289]. Furthermore, several recent studies found that hindlimb lameness localised to the distal tarsus or proximal phalanx[290] as well as that originating from the stifle[291], were correlated with decreased angles between the distal phalanx (coffin bone) and solar surface of the hoof. Excessively long toes (and, thus, small hoof angles) have also been linked to gluteal pain in horses presenting with poor performance[270]. In the forelimbs, a broken back hoof-pastern axis (characterised by long toes and low heels) was found in 73% of forelimb lame horses[292]. Breakover durations were not reported in the paper but it could deduced that the breakover durations of these hooves would also have been prolonged as a result of the unusual hoof morphology, in agreement with the results of the current study.

The findings of these and other publications in the literature, 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 cause or effect relationship[291], with it being unknown whether low hoof angles preceded the onset of lameness or vice versa[290]. Applying this rationale to the current study, it is unclear whether the increase in breakover duration preceded the onset of lameness or was a result of lameness. This is something which should be researched in the future.

In equestrian sports, *engagement* is a highly desirable component of gait quality[293]- the way the horse moves according to functionality and form[293]. This refers to how well the horse carries its weight over the haunches and is thus linked to the function of the hindlimbs, which must be able to push actively and evenly, and flexion of the lumbosacral joint to generate propulsive forces[29,294,295]. In dressage, engagement is imperative to enable the horse to achieve the collection of gait necessary to perform advanced movements and in jumping it allows the horse to realise the upward trajectory needed for clearing high fences[272]. In studies of the subjective indications of sacroiliac joint pain in horses, a decrease in engagement of the hindlimbs has been found to accompany hindlimb lameness[29,296]. Clayton[272] described acute hoof angles causing a slower, protracted breakover which resulted in a loss of engagement as the trunk moved more caudally over the weight-bearing limb. The prolonging of breakover duration identified in this study may also contribute to the reduction of engagement seen in the presence of lameness.

The result of increased breakover duration with lameness agrees with a previous study which found that breakover at walk increased with the induction of Grades 1 (+2ms), 2 (+3ms) and 3 (+1ms) lameness, compared to baseline values[205]. However, that publication did not report any differences between the lame and contralateral limbs and the magnitude of the differences reported were significantly smaller than the differences found in the current study. There are several reasons why our results may differ from the previous. Firstly, the earlier study recorded data over a surface which had been 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[297] travelling up the painful limb and thus reducing the need for the horse to adopt as pronounced a 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 a substantial effect, with Moorman et al.[205] using one model of sole pressure to induce unilateral lameness in six sound Quarter horses. Whilst this method has been widely used to induce a reversible lameness, where the degree of severity can be carefully controlled[36,51,124], we propose that the compensatory mechanisms it induces may not be truly representative of those adopted by horses suffering spontaneous lameness, (as was the case of horses in the current study, see section 4.5 Appendix) the causes of which can be many varied and complex. For instance, hoof capsule distortion (where there are permanent alterations to hoof shape in response prolonged exposure to abnormal load distribution[269,298–300]) is known to commonly accompany lameness[300].

In two recent studies[290,291], the affected limb in cohorts of spontaneously hindlimb lame horses were found to have a broken-back hoof-pastern axis, the most common hind hoof conformation abnormality. This remodelling due to long-term and chronic lameness cannot be replicated by short-term, transient lameness models. In the case of the two studies cited, the long toe would, interestingly, also tend to prolong the breakover duration of the lame limb.

At walk, the standard deviations of breakover duration were large for all groups, ranging from 17ms to 22ms, reflecting the highly varied nature of both the sound and lame cohorts. As the phenomenon is greatly dependent on individual hoof-shape[272] as well as the overall stride duration and, thus, morphology of the horse, breakover duration could vary substantially between subjects. Hence, the actual mean values of breakover duration might prove to be a horse-specific characteristic. 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.

Long toe and low hoof angles have been widely reported to pose an increased risk of injury to the distal limb as higher tensile stresses will be experienced by the DDFT and, subsequently, the navicular bone and navicular bursa will undergo higher compressive stresses. The PoB (Fig 4.1) describes the most cranial location of the hoof capsule that contacts the ground and it is the last part of the hoof capsule to leave the ground at the end of the stance[270,271]. Considering the implications of long toes on musculoskeletal health, many farrier techniques seek to 'ease' breakover, by moving the PoB caudally and to a perpendicular distance closer the centre of rotation of the coffin bone, reducing the extending moment arm and hence reducing the stresses in the distal limb during breakover. Trimming of the hooves is known to have a significant effect on the mechanism of breakover, with reductions of 30% for the distance measured from the tip of the coffin bone to the PoB[301]. Although it could be hypothesised from these results that trimming the hooves may significantly reduce the breakover duration, the parameter was not reported in the paper. Different designs of therapeutic shoes have also been promoted as a means of 'easing breakover'. In one study, the DIP joint moment arm was found to be significantly (p<0.01) reduced from 86(6)mm when the forelimbs were shod with standard, toe-clip shoes to 78(9)mm for quarter-clip shoes and 77(7)mm for Natural Balance shoes[273]. However, no significant reduction in the breakover duration accompanied these results. These observations suggest that, when using the methods of breakover duration analysis described in this chapter, one should bear in mind the hoof condition of the horse, including how recently the hooves were trimmed, whether the horse is shod and, if so, what shoes are used. In future validation studies of the methods, it would be beneficial for these and details about the morphology of the horse's hoof (such as hoof wall angles) to be recorded to better understand the potential implications. However, as the left and right hooves of contralateral limb pairs tend to be trimmed at the same time and undergo the same shoeing treatment, it is anticipated that the methods of left-right breakover duration symmetry analysis will hold, regardless.

The pairs of outliers identified in Fig 4.3 (top right panel), for the sound and lame limb pairs were attributable to the same two horses (the forelimbs of sound Horse 4, and forelimbs of lame Horse 8). These were the two biggest horses studied (178cm and 174cm, respectively); thus, it is suggested that the high breakover durations observed were due to the horses having longer total stride durations because of their height. Furthermore, despite appearing as outliers, both horses follow the pattern of their respective groups- Horse 4's forelimbs having similar breakover durations and Horse 8's lame forelimb demonstrating a longer breakover duration compared to the contralateral limb.

In summary, it was found that the symmetry of stance duration was upheld for both sound and lame horses at walk and trot. Furthermore, sound horses demonstrated symmetrical breakover durations in both the fore and hindlimb pairs at walk and trot; symmetry of breakover durations was also upheld for lame horses at trot but there was a breakdown in this symmetry at walk, where the breakover duration of the lame limbs was found to be significantly longer than that of contralateral limbs. In light of these findings, the following results and discussions focus only on the breakover durations of sound and lame horses recorded for walk.

Studying results at group level, whether the left or right limb of each contralateral pair demonstrated a longer breakover duration was not of interest; hence absolute mean differences of breakover duration, $|\overline{\Delta T_{BO}}|$, of sound, lame and opposite limb pairs were investigated at walk. For sound limb pairs there was a small value of $|\overline{\Delta T_{BO}}|$ (Fig 4.4, 6(5)ms) which seems to confirm the well-reported fact that horses do demonstrate some degree of natural asymmetry due to sidedness[113,302,303]. As a direct practical application of these results, the $|\overline{\Delta T_{BO}}|$ value for sound limb pairs could be used to establish a threshold of allowable difference to enable differentiation between natural sidedness and lameness. However, a larger cohort of sound horses would be needed to ensure robustness and generalisability of these results.

In contrast to the sound group, the $|\overline{\Delta T_{BO}}|$ value obtained for the lame limb pairs at walk (Fig 4.4, 21(5)ms) was more than three times greater ($p<0.001$), indicating a much higher degree of asymmetry. The $|\overline{\Delta T_{BO}}|$ for the opposite limb pairs (7(5)ms) was equivalent to the value obtained for sound limb pairs ($p=0.7$) and 67% smaller ($p<0.001$) than that obtained for lame limb pairs. The degree of symmetry of opposite limb pairs being comparable to that of sound indicates there was not an observable compensatory effect on the breakover duration of the opposite limb pairs in response to lameness in the lame limb pair. In studies of upper body movement symmetry, compensatory lameness mechanisms are widely reported and methods of lameness quantification which use upper body parameters can thus be complicated by compensatory effects. For instance, true hindlimb lameness often induces a compensatory lameness in the ipsilateral forelimb, which can be mistaken as the source[82]. Thus, if the methods of breakover analysis are developed for the purpose of classifying lameness, they may prove more robust against the difficulty of compensatory lameness than methods dependent on upper body symmetry.

If the proposed methods are not affected by complications of compensatory lameness, this may make them more straightforward to apply than some current subjective methods. For instance, the 0-5 AAEP scale uses a process of elimination, requiring the horse to be assessed under various different test conditions to ascertain under which conditions lameness is apparent. These conditions may include, but are not limited to, tests at walk and trot, in straight lines and circles, on flat and inclined surfaces, on hard and soft surfaces and under saddle and not. Using observations under different test conditions, the clinician may be able to identify compensatory lameness and rule these out[90,91]. If the methods of breakover analysis do prove unaffected by compensatory mechanisms, these will surely be advantageous. In future studies, the effects of different conditions (such as those used in AAEP exams) could be investigated to understand their effect on breakover duration.

The two outliers seen in the lame and opposite limb pair groups (Fig 4.4) 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 in terms of actual $|\overline{\Delta T_{BO}}|$ values, the behaviour of Horse 9 fitted the cohort pattern in terms of pairs.

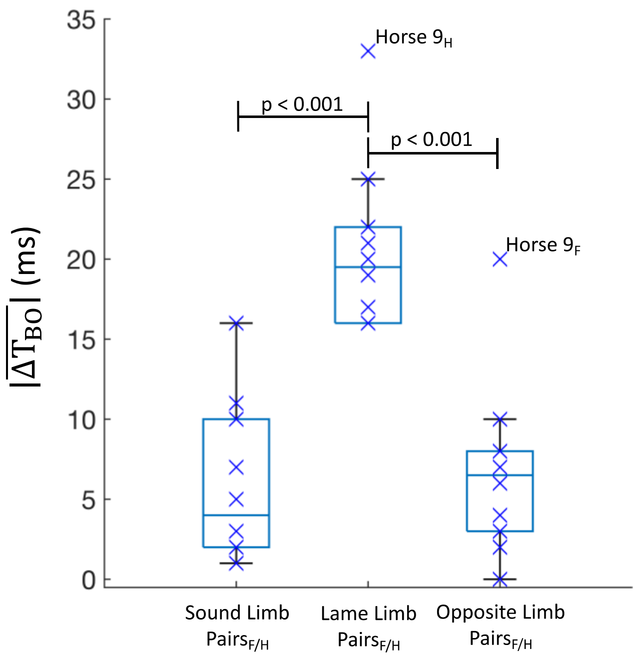


Figure 4.4 absolute mean values of the difference in breakover durations ($|\overline{\Delta T_{BO}}|$, ms) of fore (F) and hind (H) limbs for sound, lame and opposite contralateral limb pairs. Significant p-value results of unpaired Student's t-test (sound/lame) and paired Student's t-test (lame/opposite) are given. Data points from each limb pair are provided as crosses. The horse and limb pair to which outliers belong are indicated with a label.

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 limb 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. Hence, comparing concurrently recorded breakover durations of the left and right limbs of the contralateral pair is a very promising tool to detect and monitor unilateral-dominant lameness.

4.3.2 Breakover duration as a tool for lameness detection

A further example of how breakover data could be used to classify lameness in individual horses is presented in Table 4.3. At this stage, the sign of $\overline{\Delta T_{BO}}$ was included, to indicate whether the left or right limb of the contralateral limb pair demonstrated a longer breakover duration and Horse 16, (which was profoundly lame in both LF and RH) was included. 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 (Table 4.3, bold values). Sensitivity analyses indicated 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 (Fig 4.5, bottom panels). For sound limb pairs, p-values did not converge to a steady value, regardless of the number of strides analysed, which was expected (Fig 4.5, top panels). Thus, it is advised that a minimum of thirty strides be recored for application of these methods.

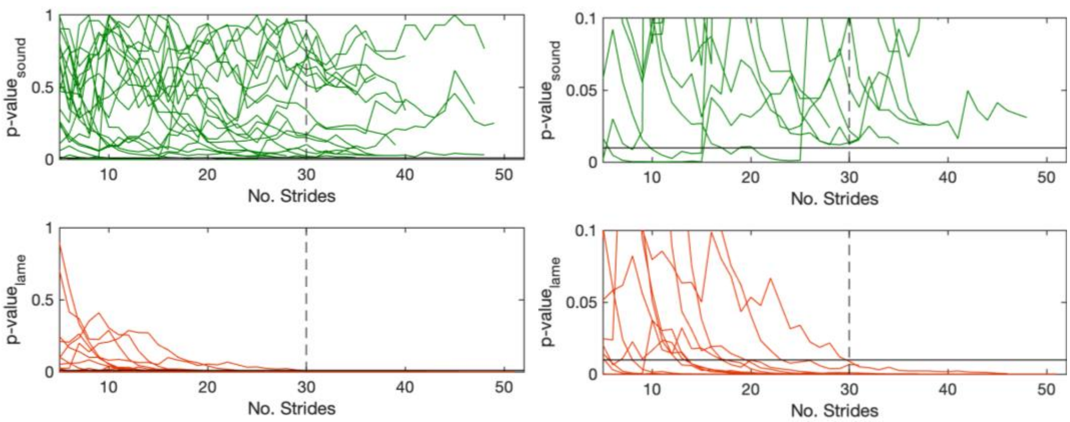


Figure 4.5 sensitivity analysis of p-value as a function of number of strides. Top panels show behaviour of p-value with number of strides for sound limb pairs (green, one line for each sound limb pair), and bottom panels

for lame limb pairs (red, one line for each lame limb pair). Panels on the right are a zoomed-in view of those on the left. Horizontal line indicates the p=0.01 threshold to differentiate significant differences from not, and vertical line indicates the minimum number of strides (thirty) chosen based on this sensitivity analysis.

Table 4.3 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, which had lameness predominating in both the left fore and right hindlimb, is presented in the bottom row.

	Horse ID	Forelimbs $\overline{\Delta T_{BO}}$(ms)		Hindlimbs $\overline{\Delta T_{BO}}$(ms)		Clinical observations
		Mean(sd)	p-val	Mean(sd)	p-val	
Sound	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
Fore. lame	6	**21(34)**	**<0.001**	3(34)	0.4	R
	7	**20(18)**	**<0.001**	2(17)	0.3	R
	8	**16(33)**	**0.006**	-4(36)	0.5	R
Hind. lame	9	-20(38)	0.01	**-33(32)**	**<0.001**	L
	10	-7(22)	0.03	**16(14)**	**<0.001**	R
	11	-8(16)	0.02	**22(21)**	**<0.001**	R
	12	0(17)	0.8	**25(18)**	**<0.001**	R
	13	-7(15)	0.02	**16(26)**	**<0.001**	R
	14	-10(40)	0.3	**19(16)**	**<0.001**	R
	15	6(36)	0.3	**-17(24)**	**<0.001**	L
	16	**-51(23)**	**<0.001**	**13(12)**	**<0.001**	LF,RH

No lameness was detected for the fore or hindlimbs of the five sound horses (Table 4.3, rows 1-5 p>0.01). The method correctly classified all the lame horses, with limb pairs where lameness was prevalent displaying statistically significant differences in breakover duration. For both fore and hindlimb lame horses, $\overline{\Delta T_{BO}}$ values of the lame limb pairs were substantially larger in magnitude than those of opposite limb pairs (Table 4.3). 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 previous 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 unilateral lameness of the left forelimb and hindlimb lameness predominating in the right hindlimb. This was one of only three horses which had been deemed lame enough to be out of work. The severity of Horse 16's left forelimb lameness appears to be reflected in the magnitude of $\overline{\Delta T_{BO}}$

(51ms), the highest recorded for the cohort. Future studies should determine whether the magnitude of $\overline{\Delta T_{BO}}$ is correlated with the severity of lameness. The results of Horse 16 also indicate that the proposed methods might be used to assess more complicated lameness cases than single-limb. Provided one limb of each contralateral limb pair is sufficiently more affected than the other as to allow detection of the asymmetry, the method may be useful for identifying lameness in concurrently fore and hindlimb lame horses. Further studies on larger populations of horses, with complex multi-limb lameness, are of course needed to support this hypothesis.

In all cases of lameness, the sign of $\overline{\Delta T_{BO}}$ correctly identified which limb of the contralateral limb pair (negative $\overline{\Delta T_{BO}}$ indicating the left limb, and positive indicating the right) was the predominantly lame. Thus, using this approach, all horses were correctly classified as sound or lame, and where lameness was present, the predominant source was identified. Further developments of the methods as a means of classifying lameness are hence justified.

Recently, a system of hoof-mounted IMUs has been developed for the specific task of quantifying hoof movement, including the temporal parameters of breakover and stance duration, and kinematic features of hoof motion (Werkman Black™, Werkman Hoofcare BV, Eemshaven, The Netherlands)[283]. Thus far, this system has been tested and promoted for use in assessing the effect of different farriery techniques on breakover duration[279] on a small cohort (n=10) of sound horses. However, the development and commercialisation of this system surely supports the proposal of the development of a similar system for the application of lameness detection and quantification.

4.3.3 Limitations and future work

The size of the cohort used in this study, while substantially larger than many similar studies in the literature[205,208], was of course small. However, the results obtained are extremely useful as they allowed sample size calculations to be conducted. Indeed, using $|\overline{\Delta T_{BO}}|$ values for sound (n=5) and lame (n=4) forelimb pairs, and sound (n=5) and lame (n=8) hindlimb pairs, calculations revealed that, to verify there exists a real significant difference between the $|\overline{\Delta T_{BO}}|$ of sound and lame forelimb pairs (power 80%, α=0.05) and between sound and lame hindlimb pairs (power 90%, α=0.01), cohorts of fourteen sound and seventeen forelimb lame, and eight sound and five hindlimb lame horses, respectively, would need to be recruited. By repeating breakover duration analysis on these larger cohorts of horses, researchers could confirm the observations made in this preliminary study and use the results obtained to establish threshold values of $|\overline{\Delta T_{BO}}|$ to classify lameness states, differentiating fore or hindlimb lame horses from sound. This should be the focus of future refinements of these methods. In addition, future studies would benefit from more attention being paid to the hoof shape and shoeing, with these factors having been reported to have an effect on breakover.

An idea for presenting the results of a larger validation study is provided in Fig 4.6. Individual datapoints are represented by markers and the coloured squares were created based on the values of these, as per the following methodology. The panel on the right shows a zoomed in view of the panel on the left.

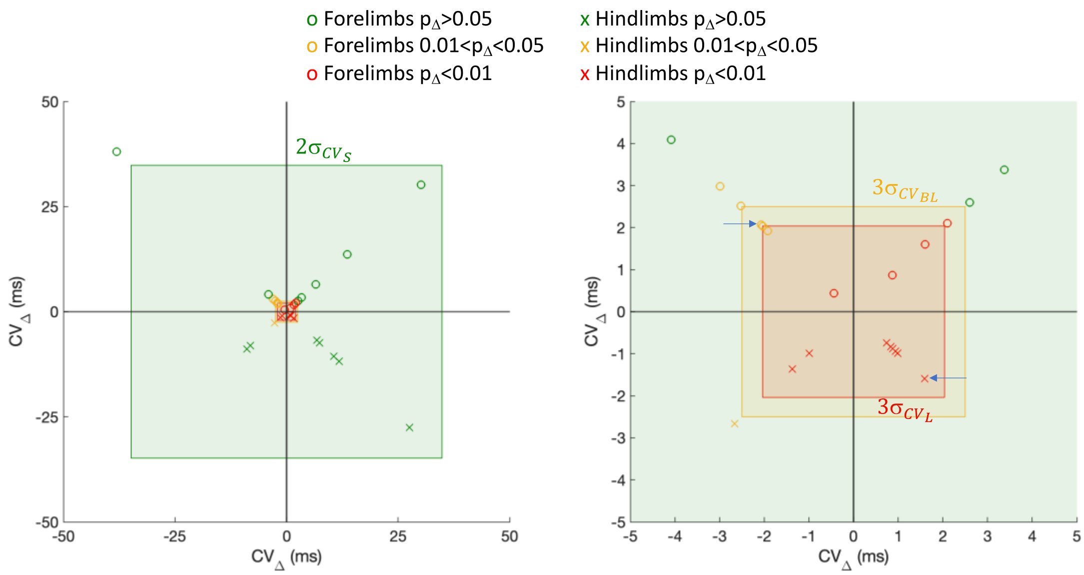


Figure 4.6 suggestion of how the results of methodologies might be presented, based on the coefficient of variation (CV$_\Delta$) of values of ΔT_{BO}. Datapoints calculated from forelimb limb pairs appear in the positive y quadrants (circles), those from hindlimb limb pairs in the negative y quadrants (crosses). Marker colours indicate the group to which the point is assigned, according to the p_Δ value, where green indicates p_Δ>0.05, yellow 0.01< p_Δ<0.05 and red p_Δ<0.01. Green, yellow and red boxes are formed based on the standard deviations of absolute CV$_\Delta$ values for green, yellow and red marker points, respectively. The chosen limits of each box are indicated by labels appearing at the boxes' edges. The panel on the right shows a zoomed in view of that on the left. Points indicated by blue arrows have been selected for illustration of how the figure should be interpreted.

After calculation of $\overline{\Delta T_{BO}}$ for each limb pair, differences were tested for significance using a paired Student's t-test and the p-value (p_Δ) was used to group values of $\overline{\Delta T_{BO}}$ (Table 4.4). When p_Δ was greater than 0.05 or less than 0.01, the limb pair was deemed sound or lame, respectively. It is hypothesised that, when larger groups of horses with varying degrees of graded lameness are tested, limb pairs falling between p_Δ values of 0.01 and 0.05 will be the borderline cases, where very early stages of lameness might be present. Thus, the condition (sound, borderline or lame) is assigned based on the value of p_Δ.

Table 4.4 details of how p_Δ is used to decide the condition- sound, borderline or lame- of the limb pair.

	Condition	Subscript	Colour
$p_\Delta > 0.05$	sound	S	green
$0.01 < p_\Delta < 0.05$	borderline	BL	yellow
$p_\Delta < 0.01$	lame	L	red

The coefficient of variation of the $\overline{\Delta T_{BO}}$ values (CV_Δ) was then computed for each limb pair, according to Eq 4.3, where μ_Δ and σ_Δ are the mean and standard of the $\overline{\Delta T_{BO}}$ values calculated for each limb pair.

$$CV_\Delta = \frac{\sigma_\Delta}{\mu_\Delta} \qquad (4.3)$$

In Fig 4.6, for each fore and hindlimb pair, a datapoint is plotted at (x,y) coordinates of (CV_Δ,$|CV_\Delta|$) and (CV_Δ,$-|CV_\Delta|$), respectively. Thus, points corresponding to forelimb pairs (circles) and hindlimb pairs (crosses) appear along the positive and negative y-axis, respectively (Fig 4.6).

Green, yellow and red squares were plotted based on values of CV_Δ. For each of the three groups- sound, borderline and lame- the standard deviation of the values of absolute CV_Δ were calculated; these are denoted σ_{CV_S}, $\sigma_{CV_{BL}}$ and σ_{CV_L}, respectively. The squares were constructed based on limits of two multiples of the value of σ_{CV_S} (green box), in which sound limb pairs are expected to fall and three of the values of $\sigma_{CV_{BL}}$ (yellow box) and σ_{CV_L} (red box) in which the borderline and lame limb pairs are expected to fall, respectively.

By constructing this figure based on a larger normative dataset collected from a cohort of sound and lame horses, with varying degrees of lameness, it is expected that a plot such as that shown (Fig 4.6) will allow the simple classification of future limb pairs assessed using the methods. Once a value of CV_{Δ} is calculated for a limb pair, it can be plotted on the figure. Values of CV_{Δ} associated with a fore or hindlimb pair will be plotted along either the positive or negative y-axis, as mentioned above. The square- green, yellow or red- in which the point falls will indicate the lameness classification of the limb pair. Whether lameness predominates in the left or right limb of the pair will be indicated by whether the point falls along the negative or positive x-axis, respectively. For example (Fig 4.6, right panel), the yellow circle indicated by a blue arrow would be interpreted as a case of possible left forelimb lameness which may warrant clinical investigation; the red cross highlighted with a blue arrow would indicate right hindlimb lameness.

Looking further ahead, once a more comprehensive validation of the methods for classifying lameness from data recorded on straight lines has been achieved, researchers could investigate the effects of curvilinear locomotion on breakover duration. Exercise in circles forms a significant part of both training and lameness workups[29]. To the best of the author's knowledge, the characteristics of breakover during circling has gone totally unreported in the literature. It is anticipated that circling may cause significant changes to the breakover durations, especially to the left/right symmetry, in all horses, so the effects of circling on breakover durations in clinically sound horses must first be understood before investigating alterations imposed by lameness.

4.4 Conclusion

Stance duration symmetry was found to be maintained for sound and lame horses at walk and trot, while symmetry of breakover duration, seen in sound horses at walk and trot, was preserved for lame horses at trot. However, lameness was found to have a significant effect on the left/right symmetry of breakover duration in affected contralateral limb pairs at walk, with lame limb having longer breakover duration compared to contralateral. With further validation, this finding will form the basis of a very valuable tool for detection and assessment of lameness. This tool may be favourable over some currently available methods as it requires the horse to be assessed only at walk, making it safe for use even in severe cases of lameness when steady trot may not be achievable.

4.5 Appendix - Details of Chapter 4 Cohort

Table A2.1 additional details of the cohort used in Chapter 4. Age (years), height (cm), breed (ISH=Irish sports horse; Welsh C=Welsh Section C) and sex (m=mare; g=gelding) of the horses are provided as well as what the horse's main use was (where details in brackets indicate the highest level the horse competed at and BE=British Eventing). If the horse was currently in work or shod (y=yes; n=no) is given. The lameness history, as provided by the owner, is detailed and which leg was most affected, in cases of lameness (LF=left fore; RF=right fore; LH=left hind; RH=right hind). Horses are organised into groups of sound, forelimb lame, hindlimb lame and one horse (Horse 16) which had severe lameness in the LF and RH.

	Horse	Age (yrs)	Height (cm)	Breed	Sex	Main use	In work	Shod?	Lameness history	Most affected limb
Sound	1	13	150	Cob	m	Dressage (Medium)	y	n	n/a	n/a
	2	5	168	ISH	m	Eventing (BE100)	y	y	n/a	n/a
	3	17	148	Welsh C	m	Low level schooling	y	y	n/a	n/a
	4	4	178	ID	g	Low level schooling	y	front	n/a	n/a
	5	6	168	ISH	g	Evening (2*)	y	y	n/a	n/a
Forelimb Lame	6	14	168	ISH	g	Eventing (5*)	y	y	Chronic mild lameness RF; still schooling and competing at high level	RF
	7	21	147	ISH	g	Eventing (BE100)	y	y	History of chronic lameness; diagnosed bilateral pedal osteitis in fore feet; most affecting RF	RF

	8	14	174	Warm-blood	g	Low level dressage	y	y	Recovering from acute tendon injury to RF	RF
Hindlimb Lame	9	5	166	ISH	m	Eventing (BE100)	y	y	Suffering acute LH lameness after sustaining injury to hock in fall	LH
	10	18	170	ISH	g	Retired eventer (2*)	y	y	Chronic lameness due to arthritic changes in hocks most affecting LH	LH
	11	16	168	ISH	g	Hacking	y	y	Arthritic changes throughout; kissing spine; presenting as RH lame	RH
	12	16	156	ISH	m	Low level schooling	y	y	Kissing spine; presenting as RH lame	RH
	13	8	166	West-falian	m	Low level schooling	y	y	Presenting moderately RH lame due to pain associated with kissing spine	RH
	14	16	158	ISH	g	Low level schooling	n	y	History of significant chronic hindlimb lameness most affecting RH; diagnosed bilateral navicular in forelimbs; recently recovered from acute injury to LF shoulder	RH
	15	18	165	ISH	m	Retired showjumper (jumping <1.60m)	n	y	Severe chronic lameness in all limbs; bilateral lameness in forelimbs due to flat, sore feet; significant hindlimb lameness due to tenosynovitis most prevalent in RH	RH
	16	14	168	Warm-blood	m	Medium dressage	n	n	Acute, severe, undiagnosed lameness in LF and RH	LF,RH

Chapter 5 Association Between Breakover Duration and Upper Body Movement

5.1 Introduction

The upper body motion of the horse at walk and trot is biphasic, with two vertical oscillations per stride cycle[25]. During trotting, anatomical landmarks along the midline of the upper body move in unison, with troughs in vertical displacement corresponding to the midstance of the left- and right-diagonal limb pairs, consecutively. In a sound horse, these two peaks are expected to have similar amplitudes; however, when unilateral lameness arises, there is degradation in the symmetry, with the vertical motion of the upper body expected to reduce during the stance phase of an affected limb pair and possibly increase during that of the other[25]. By this mechanism, the horse redistributes loading away from a painful limb. Thus, the quantification of upper body movement symmetry is often used as a means of detecting lameness[29].

Various methods have been proposed in the literature to quantify upper body movement symmetry including signal decomposition of the dorsoventral displacements[61,210,218] or accelerations[221,235,236] of the upper body. These are based on the theory that vertical upper body movement consists of three components: the biphasic one, mentioned above, a possible phasic feature arising due to unilateral lameness, and a low-frequency component caused by extraneous events such as the horse spooking. These methods have been successfully used to determine the source and severity of lameness in mild to moderate cases of spontaneous fore (twenty-nine horses[218]) and hindlimb (thirty-two horses[304]) lameness. They proved more reliable for determining severity of lameness in forelimb lameness than hind but were successfully able to locate the source in all cases. It was reported that in a case of very severe (Grade 4 forelimb) lameness, the methods could not be used as the horse could not maintain steady gait, a prerequisite of such methods[235]. These methods have rarely been applied to data collected at walk.

Autocorrelation methods, which calculate the correlation of a signal with itself delayed in time, have previously been used to quantify gait symmetry; these also offer the possibility of determining gait regularity, a measure of the similarity of consecutive strides[224,225]. These methods have been tested for determining the severity and source of lameness at walk and trot[228], and it has been suggested that they might be most useful for assessing mild lameness at walk.

Other methods which have been proposed to quantify symmetry use the difference between the absolute minima, maxima and range of dorsoventral acceleration[49] or displacement[36,67,71,73,76,305] of the upper body. Such methods have mostly been applied to data collected from the poll[49,61,67,73,218], withers[71,73,221,235,236], sternum[224,225,305], and pelvis[72,73,75,200,305]. The poll is believed to be the position most suited to analysing forelimb lameness[61,210] while the pelvis is more adapt for hindlimb cases[306]; the withers have been proposed as an ideal location for data collection to differentiate between true and apparent, compensatory lamenesses[71].

While symmetry quantification methods have been widely applied to data collected from trotting horses, coping strategies to accommodate lameness at walk are not so well understood and very few publications aimed to quantify the effect of lameness on the upper body symmetry at walk[36]. Walk is a four-beat gait, with no suspension phase, where bipedal and tripedal support alternate. The vertical motion of the poll and croup are in phase, with the croup reaching maximum position at the midstance of each hindlimb, while the withers move out of phase, reaching their maximum at the midstance of each forelimb[25]. Although the differences in the mechanisms of walk and trot suggest that lameness will not induce the same alterations in both gaits, it was hypothesised in this study that methods of lameness detection optimised for application to data collected at trot might also be able to quantify asymmetries at walk though probably to a lesser extent[36].

In the previous chapter, it was hypothesised that lameness would cause significant alterations in breakover duration, inducing a longer breakover in the lame limb compared to the contralateral limb of the pair. Indeed, this hypothesis was proven for the assessment of walk strides. The author suggested that this phenomenon was a response to pain, as the horse sought to prolong the breakover duration of a painful limb to increase comfort in the limb. The longer breakover duration might also be linked to the lower GRFs recorded for lame limbs[36,65,66], as lower tensile forces in the DDFT would be needed to overcome the moment arm[280] created by the GRF and, hence, articulation of the hoof would begin earlier in the stance phase. It could be suggested that the asymmetry in breakover duration induced by lameness could contribute to the asymmetry of vertical upper body motion reported as characteristic of lameness.

Owing to the lack of research into the link between lameness and breakover duration, there are, to the best knowledge of the author, no publications which sought to establish the relationship between this parameter and upper body movement symmetry, although three case studies reported a breakdown in the contralateral symmetry of breakover durations at trot in severely forelimb lame horses demonstrating asymmetric gait[42,43,207]. Thus, the aim of this study was to establish whether there exists a correlation between the symmetries of breakover duration and vertical upper body motion, and how this relationship is affected by lameness. It was hypothesised that there would be a correlation between the symmetry parameter derived in the previous chapter ($\overline{\Delta \mathrm{T_{BO}}}$) and lameness scores obtained using the methods from literature described above. First, methods to quantify upper body movement symmetry were to be applied to data collected at walk and trot from IMU sensors attached to the poll and croup of a cohort of horses to determine whether methods taken from the literature could classify a group of sound and lame horses. Next, the relationship between $|\overline{\Delta \mathrm{T_{BO}}}|$ and upper body movement symmetry was established by use of linear regression methods to perform an association analysis.

5.2 Methods

5.2.1 Horses

As this was a preliminary study, a convenience sample of twenty-two horses was included, reusing data collected for Chapters 3 (six horses) and 4 (sixteen horses). These were seven sound horses, five with lameness predominating in one forelimb, fourteen with lameness predominating in one hindlimb and one horse with severe lameness in one fore and contralateral hindlimb. To aid discussion, horses were labelled according to the convention: seven sound horses (S1-7), three severely lame and out of work (SL1-3), and the twelve remaining lame horses (L1-12). The details of horses are given in Table 5.1. The horses were of various breeds and uses. As before, horses were not assessed by a clinician specifically for the purpose of the study; thus, each was assigned to the sound or lame groups based on the veterinary history provided by their owner and the grade of lameness of each horse was not obtained. For each lame horse, owners provided a history of any lameness diagnosis and treatments. For more information about the cohort, see section 5.6 Appendix.

Table 5.1 morphological characteristics of the cohort.

Horse ID	Age (years)	Height (cm)	Lameness state
S1-7	7(5)	162(11)	Sound
L1-12	15(7)	156(22)	Five forelimb lame Seven hindlimb lame
SL1-3	16(2)	164(5)	Two hindlimb lame One LF and RH lame
mean(sd)	13(7)	159(75)	-

5.2.2 Equipment

A system of six IMUs (Shimmer3 IMU) was used, sampling frequency 200Hz. All IMUs contained triaxial gyroscopes (range ±2000°/s) and magnetometers (±59Ga); two contained accelerometers of range ±16g and four had accelerometers of range ±200g, where g is the acceleration due to gravity (9.81m/s^2). The IMUs containing the lower range accelerometers were securely attached to the headpiece of a snuggly fitted bridle with tape (poll sensor) and to the point of croup using double-sided tape (croup sensor). IMUs with higher range accelerometers were attached to the lateral hoof walls of the left fore and hindlimbs of six horses (those from Chapter 3), and of all four hooves of sixteen horses (those from Chapter 4), using sticky-back hook and loop fastenings.

5.2.3 Protocol

Horses were led in-hand at walk and trot, three passes per gait, along a hard track of 35m, with the central 25m being used for data analysis. Trials where there were significant disturbances, such as the horse breaking into a different gait, were repeated. Horses were verbally encouraged to maintain the correct gait, walk or trot, but were allowed to move at a self-selected speed. The methods were reviewed and approved by The University of Sheffield Research Ethics Committee (Reference Number 033398), and owners gave informed consent for their animal's involvement.

5.2.4 Data processing

Data processing was conducted using custom written scripts in Matlab (version R2021b). Datasets were first cropped down to the central 25m of the recordings. To quantify how steady the analysed portions of gait were, the coefficient of variation, in terms of stride duration, was calculated for each trial.

Data from the hooves were processed as per previous descriptions (Chapter 4), using the angular velocities to determine instances of hoof-on (h_{on}), -off (h_{off}) and onset of breakover (b_{ov})[196,197,281]. The temporal gait parameters stride (T_{stride}, Eq 1.1), stance (t_{stance}, Eq 1.2), and breakover (T_{BO}, Eq 1.3) duration were calculated.

For the sixteen horses with IMUs attached to all four hooves, the data was further processed as per Chapter 4, calculating the absolute mean difference ($|\overline{\Delta \mathrm{T}_{\mathrm{BO}}}|$, Eq 5.1) between the breakover durations of the left ($\mathrm{T}_{\mathrm{BO}_\mathrm{L}}$) and right ($\mathrm{T}_{\mathrm{BO}_\mathrm{R}}$) limbs. Absolute values were investigated because the source of lameness (the left or right limb of the lame pair) was not of interest in this preliminary study.

$$|\overline{\Delta \mathrm{T}_{\mathrm{BO}}}| = \left|\frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{T}_{\mathrm{BO}_\mathrm{R}} - \mathrm{T}_{\mathrm{BO}_\mathrm{L}}\right)_i\right| \quad \text{where } n \geq 30 \quad (5.1)$$

For all horses, accelerations from the poll and croup sensors at walk and trot were processed using methods adapted from literature. Signals were first segmented into an exact multiple of stride cycles using hoof-on timings from the left forelimb. Accelerations were realigned into a global reference frame, with reference to the vertical component of gravity[307] to account for sensor misalignment.

To remove low-frequency features associated with extraneous events, for example the horse lifting its head artificially high during a spook, the following filtering procedure was adopted[73,210]. The vertical component of acceleration (Acc_V) was filtered using system-matched filters[210], personalised for the individual horse based on the stride frequency. The signals were first padded at both ends, padding length 25% of original signal length, using the inbuilt Matlab autoregressive function 'fillgaps', to mitigate the effects of filter transients[73]. The signal was then filtered using a zero-phase, fourth order high-pass Butterworth filter with cut-off frequency (fct_{High}) equal to $\frac{2}{3}$ times the stride frequency (Eq 5.2[73]; f_{stride}, calculated from the frequency content of the angular velocity about the mediolateral axis recorded at the hoof). This was intended to remove the low frequency content of the signal, associated with extraneous movements which were not characteristic of either the natural gait cycle or effects of lameness. The signal was then filtered using a second order, low-pass Butterworth filter with cut-off frequency (fct_{Low}) equal to 20 times the stride frequency[221,235] (Eq 5.3) to remove high frequency parts of the signals which were not characteristics of equine gait, such as noise from the interaction of internal IMU components. After filtering, padding was removed from both ends of the signal.

$$\mathrm{fct_{High}} = \frac{2}{3} \cdot \mathrm{f_{stride}} \qquad (5.2)$$

$$\mathrm{fct_{Low}} = 20 \cdot \mathrm{f_{stride}} \qquad (5.3)$$

Filtered Acc_V was then processed as per three different methods for lameness detection from literature. The first sought to establish the degree of gait symmetry by investigating the frequency content of the signal and, from this, deduce if the horse was sound or lame[210]. A Fast Fourier Transform was applied to Acc_V to obtain the frequency content. Theoretically, the poll and trunk movement of perfectly sound, symmetric gait consists of two similar dorsoventral oscillations per stride cycle, yielding a frequency content plot with one prominent harmonic at double the stride frequency (f_1). As the gait becomes more asymmetric (Fig 5.1), indicating a possible lameness, a second harmonic becomes apparent, at the stride frequency (f_0).

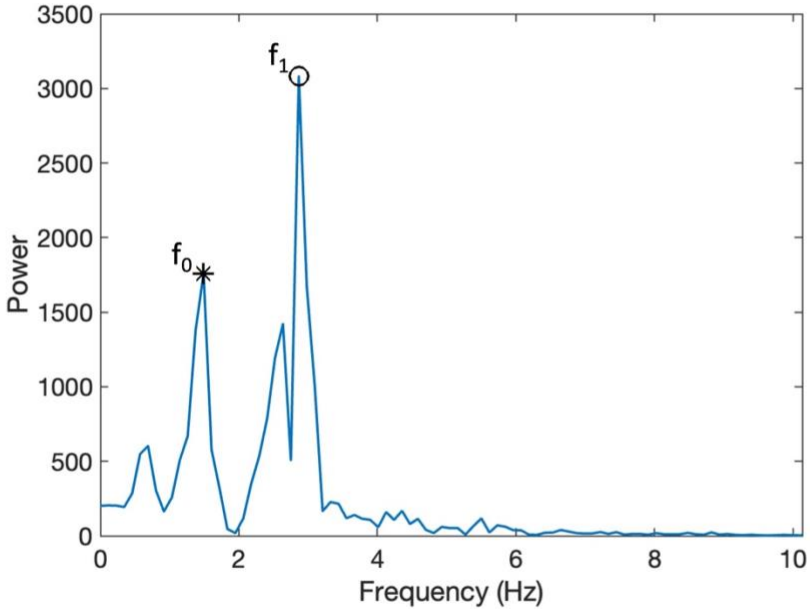


*Figure 5.1 example of the frequency content of poll Acc_v of a severely forelimb lame horse. The first harmonic (f_0, *) is related to the phasic, asymmetric component of gait associated with lameness while the second (f_1, O) is related to the natural biphasic component of gait [210].*

The relative amplitude of these components can be used as an indication of gait symmetry (SI, Eq 5.4). When the symmetric component dominates, f_0 tends to zero and SI tends to 100%, indicating sound gait. When the gait is asymmetric, indicating possible lameness, the influence of f_1 becomes more apparent and the value of SI becomes smaller.

$$\mathrm{SI} = \frac{f_1}{f_0 + f_1} \cdot 100 \qquad (5.4)$$

The second symmetry index is based on the concept that the Acc_v of the trunk is representative of the GRFs experienced by the corresponding limbs[221,235,236]. Thus, during the load bearing, stance phase of a lame limb, Acc_v is expected to be smaller than during that of a sound limb, associated with the lower GRFs experienced by a lame limb (Fig 5.2). By comparing the area under two consecutive peaks of Acc_v, asymmetries of gait can be detected. Symmetry index A (Eq 5.5) was calculated for pairs of successive peaks.

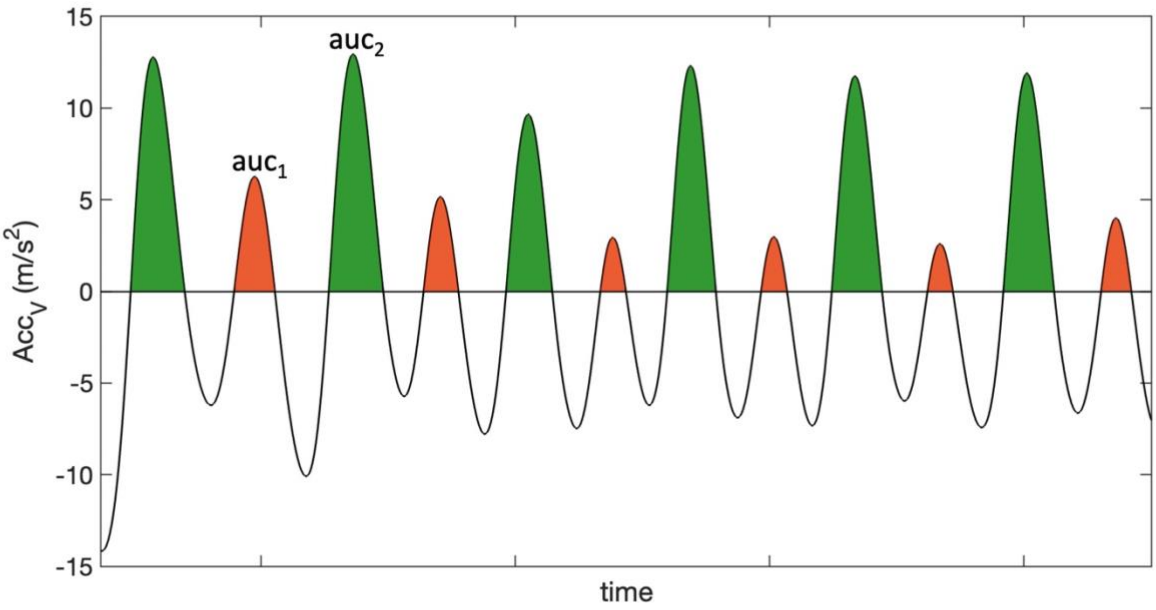


Figure 5.2 example of the filtered poll Acc_v of a severely left forelimb lame horse at trot. The stance durations of the lame, right diagonal limb pair correspond to the red peaks (auc_1), those of the left to the green (auc_2)[221].

$$A = \log\left(\frac{auc_1}{auc_2}\right) \qquad (5.5)$$

When Acc_v is synchronised with information about the temporal gait parameters, the method can be used to determine whether lameness presides in the left or right diagonal limb pair. Thus, if auc_1 is correlated to the stance duration of the right diagonal limb pair, and auc_2 to those of the left (as in example Fig 5.2), A becomes negative when lameness is present in the right diagonal limb pair and positive when it presides in the left. Perfectly symmetric gait would produce an A value of 0. In this study, whether lameness presided in the left or right diagonal limb pair was not of interest so absolute values, |A|, were investigated.

The last indices to be investigated applied methods of unbiased autocorrelation to the filtered Acc_v of poll and croup[224]. By calculating the correlation of a signal with itself delayed in time, autocorrelation indicates how similar or not a waveform is to itself over time. Hence, for walk and trot, which have two similar oscillations of Acc_V per stride cycle, gait symmetry is quantified by the first peak in the autocorrelation function (Ad1- when the signal is compared to itself delayed by a half stride cycle), and gait regularity by the second (Ad2- when the signal is compared to itself delayed by a whole stride cycle), an illustration of this is given (Fig 5.3). Perfectly symmetric gait, where the two vertical oscillations of a stride are almost identical, yields Ad1 values which tend towards one, while perfectly regular gait, where the vertical motion of successive strides are identical, yields Ad2 values tending towards one.

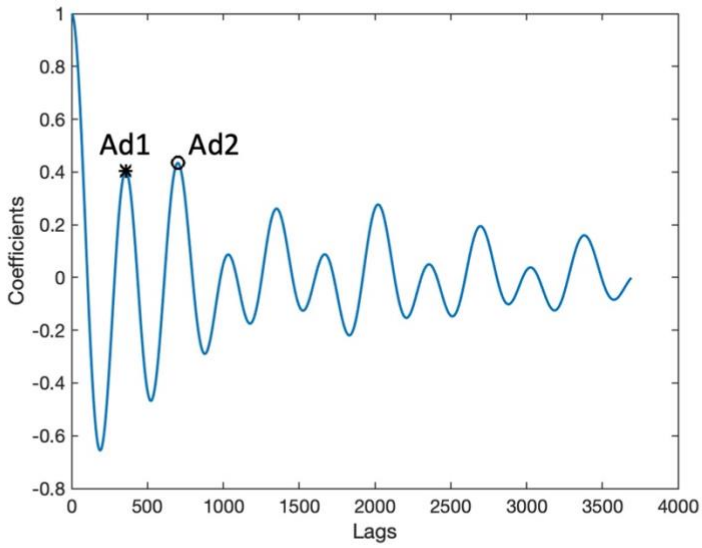


*Figure 5.3 example of the autocorrelation function obtained from the filtered Acc_V of the poll of a severely forelimb lame horse at trot. Peaks correlating to the step-by-step similarity of gait (Ad1- gait symmetry) and stride-by-stride similarity (Ad2- gait regularity) are indicated by * and ○, respectively.*

A summary of the methods and interpretation of the result is provided (Table 5.2).

Table 5.2 summary of the methods used and the interpretation of the result.

Method	Equation/Parameter	Interpretation
Frequency content	$SI = \frac{f_1}{f_0 + f_1} \cdot 100$	SI = 100%: perfect symmetry
Area under the curve	$A = \log\left(\frac{auc_1}{auc_2}\right)$	A = 0: perfect symmetry Positive A: lame left diagonal limb pair Negative A: lame right diagonal limb pair
Autocorrelation	Ad1, Ad2	Ad1 = 1: perfect symmetry Ad2 = 1: perfect regularity

Symmetry indices were calculated using these three approaches for all twenty-two horses in the cohort, analysing data recorded from the poll and croup sensors at walk and trot. The group level results of these were investigated using boxplots, to ascertain the effect of lameness on the upper body symmetry, determining whether the methods were sufficient to classify sound and lame horses and which signal (poll or croup, at walk or trot) yielded most information about gait symmetry. When differences were observed between the sound and lame groups, or between the results of walk and trot for either group, the data was first tested for normality using Shapiro-Wilks test, $p<0.01$ indicating non-normal data. Between-group differences were tested with the non-parametric Wilcoxon sign-rank (non-normal data) or unpaired Student's t-tests (normal data), and between-gait differences using Wilcoxon rank-sum or paired Student's t-tests. A threshold of $p<0.01$ was chosen to indicate where differences were significant.

Next, data from the sixteen horses of the previous study were used to understand the relationship between $|\overline{\Delta T_{BO}}|$, measured at the distal limbs, and the upper body movement symmetry, and suggest how lameness might influence this, by conducting an association analysis. The $|\overline{\Delta T_{BO}}|$ values obtained for walk were compared to the symmetry indices (SI, |A|, Ad1 and Ad2) obtained for the poll and croup sensors at trot, using methods of linear regression.

5.3 Results

The results of the first level of analysis, from the cohort of twenty-two horses, are presented; a total of 892 walk and 813 trot strides were analysed, with an average of 41(10) and 37(16), respectively, per horse. The mean coefficients of variation for stride duration were 3.31(0.95)%, range 1.96-5.08% for walk and 4.22(1.12)%, range 2.30-6.00% for trot.

5.3.1 Stride and breakover durations

Fig 5.4 presents the mean stride durations for the sound and lame horses at walk and trot. There were no between-group differences at either walk (sound 1255(41)ms; lame 1210(108)ms) or trot (sound 756(62)ms; lame 704(76)ms). The between-horse differences were large and one forelimb lame horse (Horse L4) stands out as having had a substantially shorter stride duration at both walk and trot.

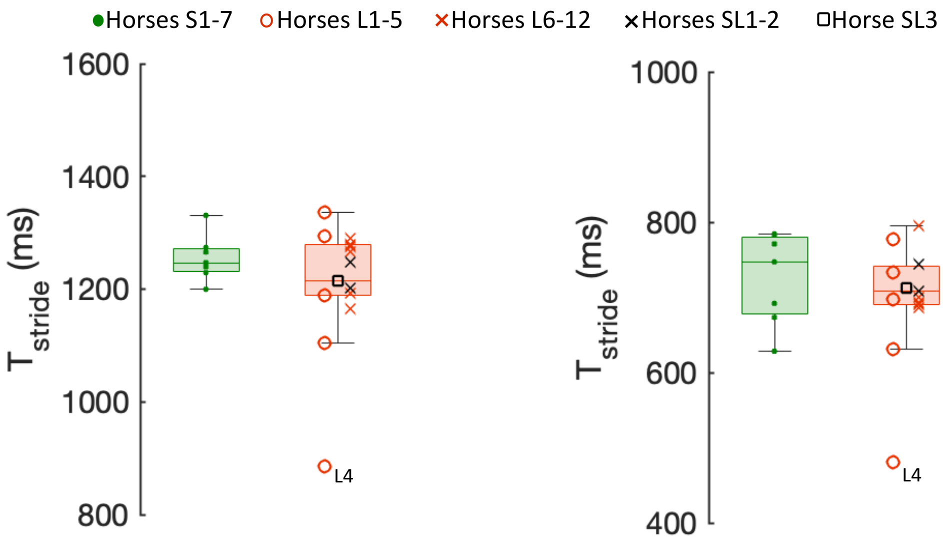


Figure 5.4: stride durations of the sound (green boxes) and lame (red boxes) cohorts at walk (left) and trot (right). Mean stride durations of individual horses are given by markers. Green dots indicate sound horses (S1-7); red circles forelimb lame (L1-5); red crosses hindlimb lame (L6-12); black crosses severely hindlimb lame (SL1-2) and black square the horse severely lame in one fore and contralateral hindlimb (SL3). The outlying forelimb lame horse (L4) is labelled.

Recall that results of the previous chapter showed breakover durations were symmetric for sound and lame limb pairs at trot and sound limb pairs at walk (Table 5.3) but that there was a break down in the symmetry for lame limb pairs at walk, with lame limbs demonstrating a significantly longer ($p<0.0001$) breakover duration than contralateral limbs.

Table 5.3 summary of Chapter 4 results. Breakover durations (ms) of sound and contralateral limbs of sound limb pairs (n=10), and lame and contralateral limbs of lame limb pairs (n=10) at walk and trot are reported. The p-value results of tests for significant between-limb differences and effect sizes are given.

Sound limb pairs	sound	contralateral	p-value	Effect size
walk	166(22)	171(17)	0.07	-0.3
trot	73(11)	74(9)	0.9	-0.02
Lame limb pairs	lame	contralateral	p-value	Effect size
walk	176(22)	146(23)	<0.0001	0.9
trot	80(10)	76(7)	0.4	0.17

5.3.2 Upper body motion symmetry

Fig 5.5 shows the results of the upper body symmetry indices calculated for the sound and lame horses, using data taken from the poll and croup sensors, at walk. At walk, there were no significant between-group differences ($p>0.01$) in the measures of gait symmetry (SI, |A| or Ad1) calculated for the poll or croup sensors.

Looking at the poll results, two horses, one forelimb lame (L3) and one severely fore and hindlimb lame (SL3), stand out as having much lower values of SI_{poll} than other horses in the cohort (81% and 76%, respectively). For SL3, values of $|A|_{poll}$ (0.62) and $Ad1_{poll}$ (0.65) also indicate a high degree of gait asymmetry. For values of $Ad2_{poll}$, the lame group appear to have demonstrated a slightly more regular gait (0.82(0.04)) than the sound (0.78(0.03)) and an unpaired Student's t-test revealed a p-value of 0.016; however, the effect size was large (0.89). There were no differences between the values of $Ad2_{croup}$ recorded for sound and lame groups. All values of Ad1, for the poll and croup of sound and lame horses, fell below thresholds previously set[225], values below which were reported to indicate 'abnormal' gait symmetry. All Ad2 values fell close to or below the threshold of 'abnormal' regularity.

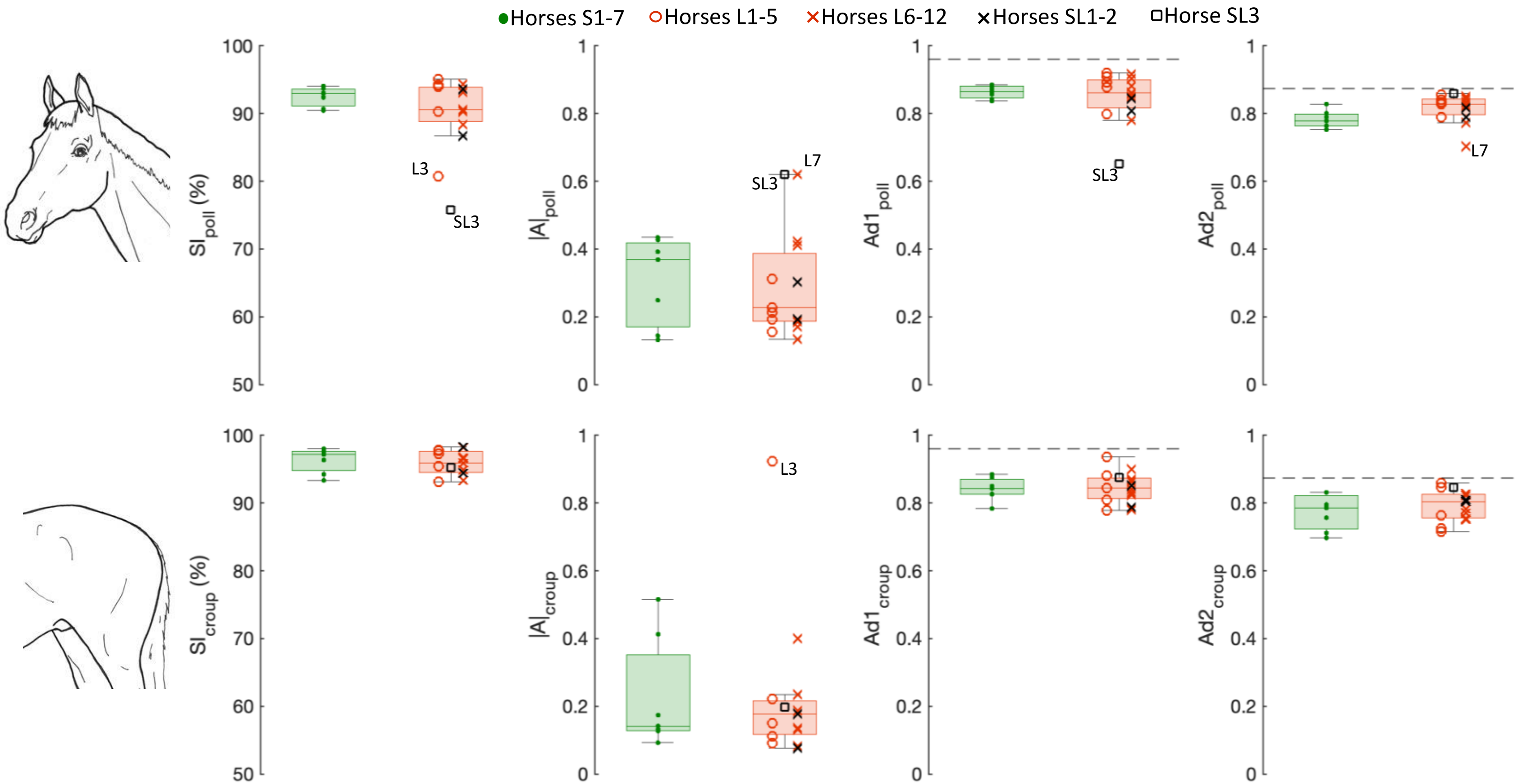


Figure 5.5 symmetry indices of the vertical poll (top) and croup (bottom) motion of the sound (green boxes) and lame (red boxes) cohorts at ***walk****. Mean symmetry indices of individual horses are given by markers. Green dots indicate sound horses, circles forelimb lame, crosses hindlimb lame and squares the horse that was severely fore and hindlimb lame. Red markers indicate lame horses (L1-12) and black indicate horses deemed lame enough to be taken out of normal work (SL1-3). Prominent outliers are labelled. The black dashed lines (Ad1 and Ad2) indicate previous thresholds for 'abnormal' gait symmetry or regularity[225]. Statistically significant differences are indicated by inclusion of the p-value.*

Fig 5.6 shows the results of the upper body symmetry indices calculated for the sound and lame horses, using data taken from the poll and croup sensors, during trotting. Here, although mean values of SI_{poll}, $|A|_{poll}$ and $Ad1_{poll}$ indicated slightly lower gait symmetry for the lame group (81(10), 0.69(0.51) and 0.73(0.17), respectively) compared to the sound, (86(4), 0.55(0.33) and 0.81(0.05), respectively), none of these differences were significant. There was no difference between Ad2 values recorded for sound and lame groups from the poll ($p=0.4$) or croup ($p=0.9$); nor were there any between-group differences in the values of gait symmetry for the croup. Lameness appears to have had the most pronounced effect on $|A|_{poll}$, with the variation in values recorded for the lame group being far higher than for any other index calculated (note the y-axis limits of 0 to 2, Fig 5.6).

For all measures of poll symmetry at trot, two of the three lamest horses (SL1 and SL3) stand out as having a substantially less symmetric gait than the rest of the cohort. The values of SI_{poll} obtained for SL2 also indicate a less symmetric gait than most of the lame horses. Of these three lamest horses, only one, hindlimb lame SL2 stood out as having substantially less symmetric croup movement than the rest of the lame group (SI_{croup}, $|A|_{croup}$ and $Ad1_{croup}$). Values of gait regularity, $Ad2_{poll}$ and $Ad2_{croup}$, for these three horses was similar to that of all others.

As with walk, all values of Ad1 for the poll and croup fell below the threshold highlighting 'abnormal' gait symmetry[225]. Values of Ad2 fell mostly below the threshold indicating 'abnormal' gait regularity with only one fore (L2) and one hindlimb (L8) lame horse registering Ad2 values above the threshold for both poll and croup.

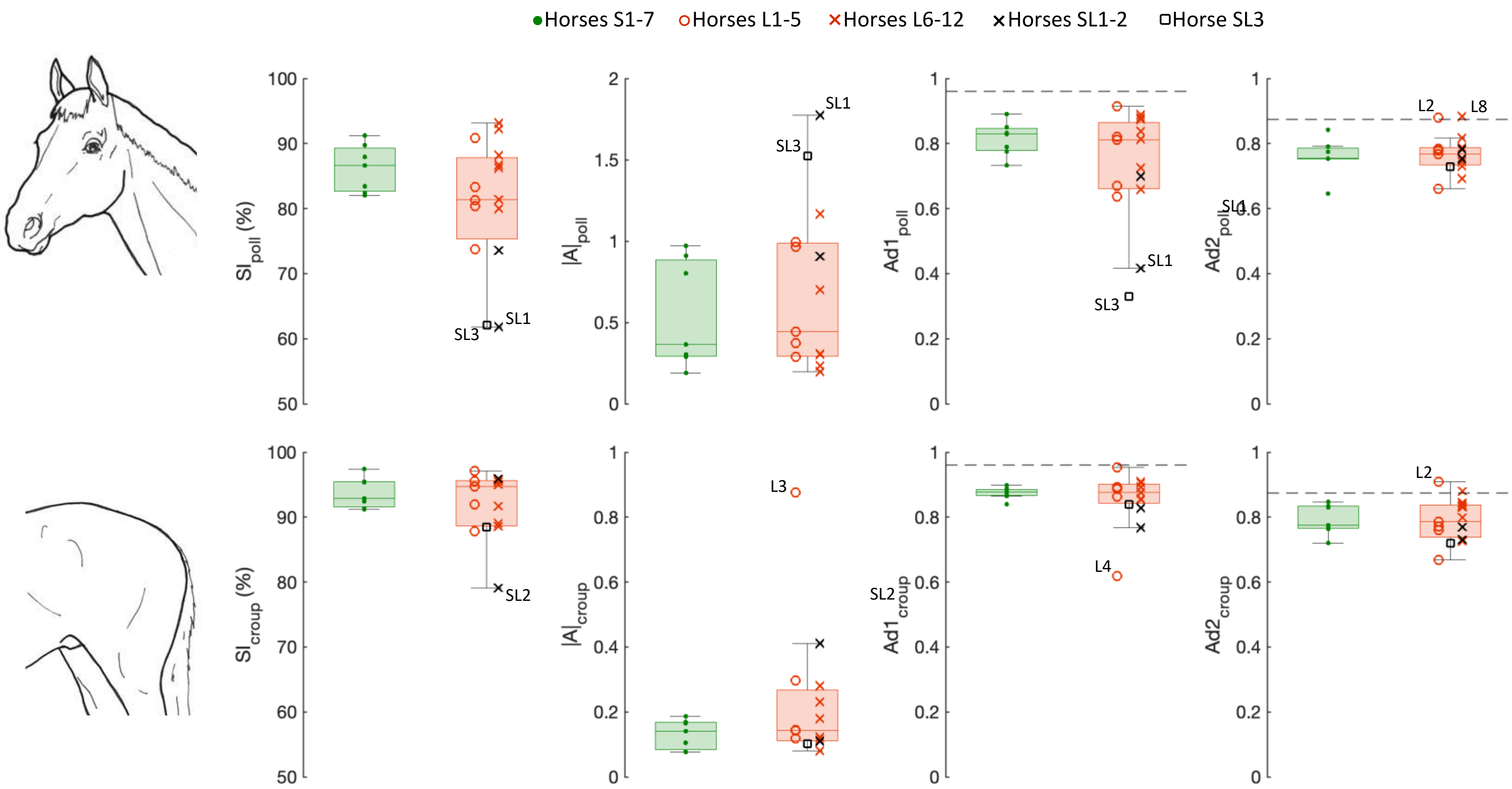


Figure 5.6 symmetry indices of the vertical poll (top) and croup (bottom) motion of the sound (green boxes) and lame (red boxes) cohorts at ***trot****. Mean symmetry indices of individual horses are given by markers. Green dots indicate sound horses, circles forelimb lame, crosses hindlimb lame and squares the horse that was severely fore and hindlimb lame. Red markers indicate lame horses (L1-12) and black indicate horses deemed lame enough to be taken out of normal work (SL1-3_. Prominent outliers are labelled. The black dashed lines (Ad1 and Ad2) indicate previous thresholds for 'abnormal' gait symmetry and regularity*[225].

Comparing the symmetry indices calculated at walk to those calculated at trot, for the lame horses there was a trend of far more between-subject variation at trot, while in contrast there tended to be a similar degree of between-subject variation for the sound group in the two gaits. The poll motion of sound and lame groups indicated a lower degree of symmetry at trot compared to walk, with differences being statistically significant for SI_{poll} in the sound group, and SI_{poll} and $|A|_{poll}$ in the lame (Table 5.4). SI_{croup} of the lame group also indicated significantly more symmetric gait at walk compared to trot (p=0.0031).

Table 5.4 results of statistical tests to determine the significance of differences between symmetry indices, (SI, |A|, Ad1 and Ad2) for sound and lame groups, calculated at walk to those calculated at trot. Test results for poll and croup symmetry indices are given. Significant results (p<0.01) are shown in bold.

p-value	sound				lame			
	SI	|A|	Ad1	Ad2	SI	|A|	Ad1	Ad2
poll	**0.0097**	0.17	0.057	0.27	**0.0025**	**0.0054**	0.031	**0.009**
croup	0.13	0.22	0.12	0.58	**0.0031**	0.80	0.17	0.97

5.3.3 Relationship between upper body motion symmetry and breakover duration

For the next level of analysis, involving sixteen horses, 700 walk and 543 trot strides were analysed, with an average of 41(10) and 34(9) strides per horse, respectively.

In Fig 5.7, the correlations between different symmetry indices are inspected. These present the relationship between the parameter derived in the previous chapter, $|\overline{\Delta T_{BO}}|$, measured at walk, with indices SI, |A|, Ad1 and Ad2 calculated using trot data from the poll and croup. Regression analysis revealed that there were no direct correlations between symmetry indices, with low values of R^2 in all cases. Across all indices, the markers from the sound and lame groups are heavily overlapped. In all cases, there appears be more overlap between sound and lame groups in the x-direction, (lameness indices calculated using upper body symmetry indices) compared to in the y-direction, (lameness index $|\overline{\Delta T_{BO}}|$). This reflects the fact that the methods described in the Chapter 4 were able to correctly classify lame and sound horses; however, using the symmetry indices based on vertical upper body accelerations, there is no distinction possible to differentiate between sound and lame horses for this cohort.

The results of $|A|_{poll}$ for the sound group tended to be more clustered around the origin than for the other indices but there was still a heavy overlap in the x-direction with horses from the lame group. Another example of clustering could be suggested for the poll results where the lame limb pairs of the lamest horses, SL1-3 marked in black, tend to appear in a cluster, showing up as having less symmetric gait than the rest of the cohort. This is most pronounced for SI_{poll} and $|A|_{poll}$. For $Ad1_{poll}$, the lamest (black, SL1-3) limb pairs still appear as distinct from all sound and less symmetric (further right on the x-axis) than many points, but overlap with one forelimb lame horse (L3, red circle). At the croup, only SL2 consistently stood out as less symmetric than all others in the cohort (SI_{croup}, $|A|_{croup}$ and $Ad1_{croup}$).

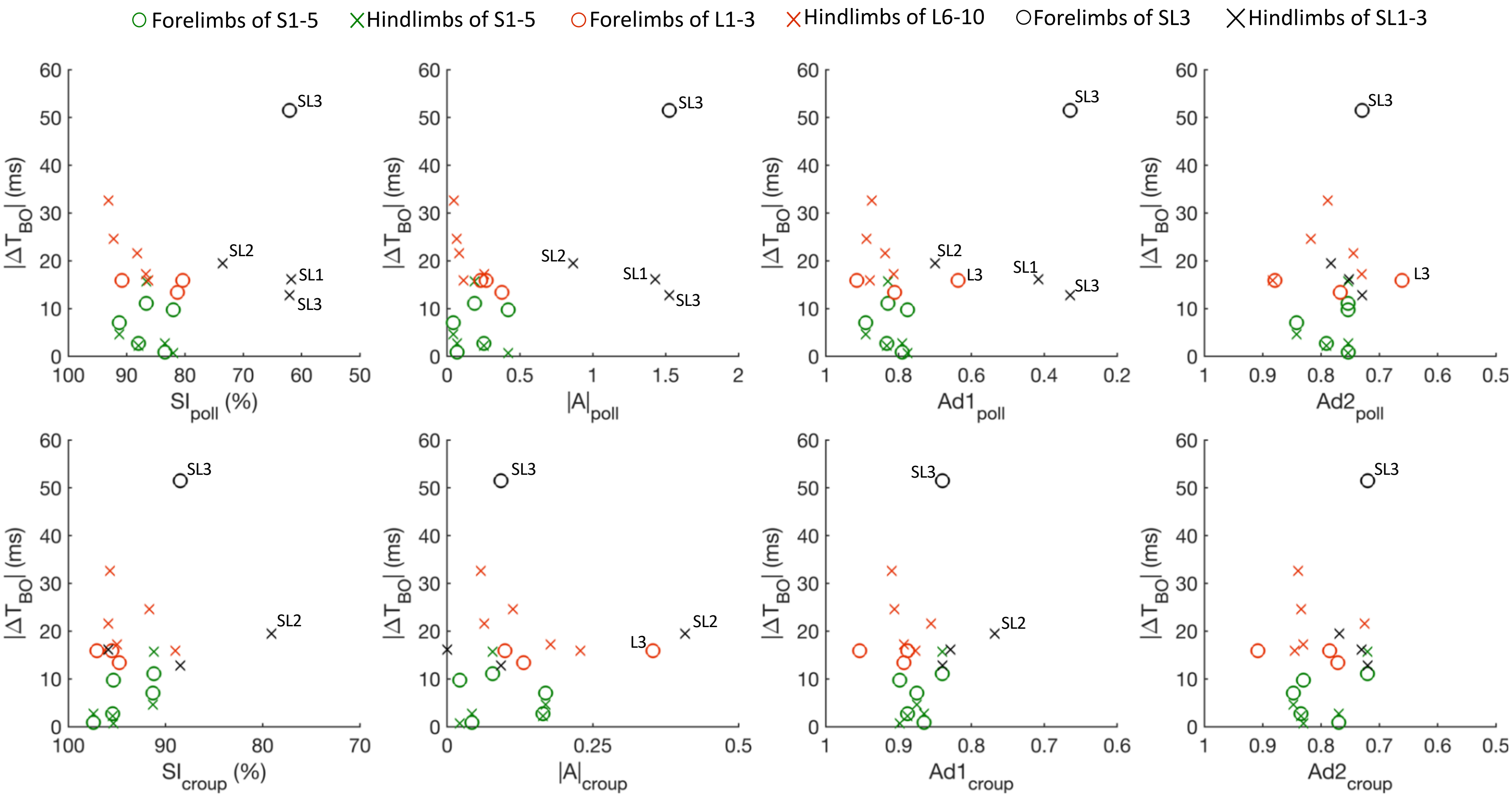


Figure 5.7: correlation plots of mean $|\Delta T_{BO}|$, calculated for walk, with mean indices SI, |A|, Ad1 and Ad2 calculated for the vertical poll (top panels) and croup (bottom panels) accelerations at trot. Circles indicate the values obtained for forelimb pairs and crosses those for hindlimb pairs. Green markers indicate sound horses (S1-5), red lame horses (L1-3 and L6-10) and black those deemed lame enough to be out of work (SL1-3). The axes of the plots are chosen such that points plotted further right along the x-axis indicate a higher degree of asymmetry (SI, |A|, Ad1) or irregularity (Ad2); and points plotted further along the y-axis indicate a higher degree of asymmetry in the left-right breakover durations of the contralateral limb pair. Prominent outliers are labelled.

5.4 Discussion

The aim of this study was to establish whether there is a trend between the symmetries of breakover duration and vertical upper body motion, and how this relationship is affected by lameness. Before investigating this, methods to quantify upper body motion symmetry were explored, establishing which sensor location (poll or croup) is most informative of gait symmetry and verifying that trot, over walk, is the more desirable gait for symmetry analyses. The results of this preliminary study are of course limited by the sample size.

5.4.1 Stride durations

Previous studies found inducing unilateral fore or hindlimb lameness did not affect the stride durations at walk but caused significant reductions in stride duration at trot[51] on a treadmill. However, the results of the present study indicate that there was no difference between the stride durations of sound and lame groups in this highly varied cohort, measured overground, at either walk or trot. In both gaits, one forelimb lame horse (L4) stood out as having a much shorter stride duration than the rest of the group. This 90cm Shetland, was the smallest horse in the cohort by 57cm; thus, the very short stride duration was most likely due to the horse's size and the breed-specific characteristics of Shetland gait.

5.4.2 Characterising upper body movement symmetry

The mean coefficients of variation were a little higher than those reported in the literature[221] for calculating A at trot (4.22(1.12)% compared to 3.2%) but the range of values overlapped heavily (2.3-6.0% compared to 0.7-6.6%). The mean coefficients of variation recorded for walk were lower still (3.31(0.95)%, range 1.96-5.08%). The methods used to quantify upper body motion symmetry must be applied to steady gait, to yield valid results. The coefficients of variation recorded here suggest that the gait analysed was sufficiently steady for valid application of the methods.

Methods of upper body symmetry quantification, (SI, |A| and Ad1) do not appear to have been capable of differentiating between the movement symmetry of sound and lame horses in this cohort when applied to data collected at walk as there were no between-group differences. The lower GRFs experienced during[36] walk may explain why the horse does not have to alter their movement as significantly to minimise pain, compared to when trotting. Due to this, methods of lameness quantification which measure upper body motion symmetry, (such as those used here) have been optimised for analysis at trot, not walk, which could explain why the methods were unable to detect differences between groups at walk.

Nonetheless, the results of the lamest horse in the cohort, SL3, highlighted highly asymmetric gait for all symmetry indices calculated from the poll at walk. This result could suggest methods of upper body symmetry quantification are capable of detecting lameness at walk once it is in the more advanced stages but a much larger cohort of horses with various degrees of lameness, ranging from mild to severe, would need to be investigated to test this hypothesis.

For the lame group, gait symmetry was significantly lower at trot compared to walk, when measured with SI_{poll} and $|A|_{poll}$; a feature that was only seen for values of SI_{poll} in the sound group. This agrees with literature that reported a higher degree of asymmetry at trot compared to walk, for horses with induced lameness[36]; the pattern was reported for the horses before lameness induction, with healthy trot showing more asymmetry of the upper body than healthy walk, but this was less pronounced. In the current study, for both sound and lame horses there was a much higher degree of between-horse variability for poll-based symmetry indices at trot compared to those at walk, suggesting that trot data was more useful for differentiating between the different gait symmetries of individual horses. For croup data, there was higher between-horse variability for SI_{croup} and $Ad1_{croup}$ at trot compared to walk. From these results it was verified that trot was generally the preferred gait, over walk, for assessing upper body movement symmetry, in agreement with previous advice[29], especially for poll data, and that it might be better able to differentiate between different lameness states.

At trot, there were no between-group differences indicating the methods were not sufficient to classify the lameness state of many horses in the cohort. However, two of the lamest horses in the group, SL2 and SL4, along with several other lame horses, were clearly distinguishable from sound horses using poll based symmetry indices. Hence, it could be suggested that the methods are mostly effective for identifying moderate to severe lameness but might not be able to differentiate between milder cases and the natural asymmetry seen in a sound cohort.

Only SL2 was consistently distinguishable from the sound horses using each symmetry index calculated from the croup mounted sensor. Hence, data from the croup sensor appears to have been less informative than that from the poll for identifying lame horses amongst this cohort. It has been widely reported that hindlimb lameness often induces a significant, compensatory forelimb lameness[36,124] which explains why the poll motion is affected, even for horses suffering only hindlimb lameness. The head and neck account for a large proportion of the horse's weight, weighing around 10% of the body mass[69]; therefore, adjustment of the motion of these body segments is highly effective for the purpose of load redistribution. Furthermore, it is understood that the horse uses the head and neck to maintain balance[308]; thus, the author suggests that a lame horse may need to alter the motion of the head and neck to maintain balance during load redistribution.

The range of recorded values for all symmetry indices of the sound group indicate that perfect gait symmetry should not be expected, even for sound cohorts, due to the natural asymmetries seen even in healthy horses[30,243]. As expected[77], a higher degree of symmetry was seen in the croup motion compared to the poll for both sound and lame groups, as the horse has more autonomy over the poll and therefore indices calculated from this location are more susceptible to extraneous events, such as the horse lifting their head in a spook; although filtering methods had been optimised to reduce the contribution of these events, they could not be completely eradicated. These observations support the need for the development of threshold values to differentiate between degrees of natural asymmetry which are expected in animals and those which are indicative of lameness. The results of this study suggest that different thresholds are needed, specific to the location at which the data was recorded (for instance from the poll or croup, as here). These thresholds must be developed using large cohorts of horses, verified as being clinically sound.

The method of calculating SI from the frequency content of the vertical poll motion has been applied to data recorded using OMC methods in a cohort of spontaneously forelimb lame horses trotting on a treadmill[218], where values of SI_{poll} ranged from 29-90%. In the present study, SI_{poll} recorded for lame horses ranged from 62-93% indicating that results fell mostly within the boundaries of what was previously observed, with only three lame horses registering SI_{poll} values greater than 90%. However, values of SI_{poll} recorded for the sound group (82-91%) also overlap with this range. Thus, although SI_{poll} results were consistent with the literature for lame horses, it may not be a suitable symmetry index for differentiating sound from lame horses as the natural gait asymmetries of sound horses appear to overlap heavily with asymmetry due to lameness.

Previously, Ad1 values <0.96 and Ad2 <0.88 were found to indicate 'abnormal' gait symmetry and regularity, respectively, when applied to dorsoventral accelerations recorded from the sternum or croup[199] of young, sound horses at trot[225]. All values of Ad1 for sound and lame horses at trot in the current study fell beneath the threshold of 'abnormal' gait symmetry and most values of Ad2 fell on or below the threshold for 'abnormal' gait regularity, with only two lame horses at trot ($Ad2_{poll}$ and $Ad2_{croup}$) falling above. In the case of the poll, this is perhaps not surprising as a higher degree of asymmetry and gait irregularity might be expected here, compared to the sternum or croup[77] for which the thresholds were developed. However, the results of autocorrelation applied to the croup data could indicate that the thresholds set previously are too restrictive for general application to larger cohorts. Further, in a previous study dorsoventral accelerations of the sternum of one horse at trot yielded Ad1 values of 0.67, 0.55 and 0.49, and Ad2 of 0.65, 0.59 and 0.48 for sound, grade 1 and 2 lameness states, respectively[224] and still lower values of Ad1, calculated from a sternum mounted accelerometer, have been reported elsewhere[234]. These results, along with those of the current study, support the need for further refinement of threshold values to differentiate between sound and lame gait, when applying the methods of autocorrelation to accelerations recorded at different locations on the body.

In summary, trot was found to be more informative than walk for investigating symmetries of gait and, for trot, data recorded from the poll identified a greater degree of between-horse variability in gait symmetry than that from the croup. The methods applied to data recorded from the poll at trot were able to distinguish between two of the lamest horses in the cohort and the sound but, ultimately, the methods proved insufficient to correctly classify all horses, with significant overlaps in the results of the sound and lame horses.

5.4.3 Association between upper body movement symmetry and breakover duration

The hypothesis that the asymmetry recorded in the breakover duration (Chapter 4) would contribute to asymmetry of motion measured at the upper body cannot be accepted, based on these results, as no strong correlation was seen. However, a number of trends were nonetheless identified, using the results of this pilot study, which could be used for future study designs.

For sound horses, $|A|_{poll}$ appears to cluster most around the origin which could suggest that the $|A|$ symmetry score is the most useful for characterising a sound group. Markers from the lamest horses in the cohort (SL1-3), tended to cluster together for symmetry indices calculated from data collected at the poll, and were clearly distinguishable from the sound group using each poll based index, being the most extreme values recorded in each case. This indicates that these horses could have been clearly identified as lame using either $|\overline{\Delta T_{BO}}|$ (as described in Chapter 4) or any of the poll based symmetry indices. Thus, symmetry scores based on the Acc_v of the poll may be useful in identifying more severe cases of lameness. Although results of linear regression suggest that there was no direct correlation between $|\Delta T_{BO}|$ and the upper body symmetry indices when the entire lame group was assessed, the clustering of SL1-3 might indicate a relationship between $|\Delta T_{BO}|$ and vertical poll symmetry in very lame horses. Future studies could recruit a larger cohort of severely lame horses to investigate this hypothesis.

Using $|\Delta T_{BO}|$ every sound and lame horse was correctly classified (Chapter 4); the literature methods of lameness classification, applied to Acc_v of the poll or croup at trot, were not able to differentiate between sound and lame in all cases. Thus, results of this study may suggest that $|\Delta T_{BO}|$ is in fact a more sensitive parameter for detecting lameness than some of the upper body symmetry scores currently used. While there appears to be significant overlap of the sound and lame group in the x-direction (Fig 5.7), for all symmetry indices, in the y-direction there is a clearer distinction, with only a few points overlapping at around $|\overline{\Delta T_{BO}}|$=15ms. This further supports the suggestion made in Chapter 4 that, by investigating the contralateral symmetry of breakover duration ($\overline{\Delta T_{BO}}$) in a larger cohort of sound horses and horses with various degrees of lameness verified by sufficient clinical investigations, threshold values of $\overline{\Delta T_{BO}}$ might be established to enable differentiation between sound and lame horses.

In this study, methods to quantify symmetry of the vertical upper body motion proved insufficient for classifying lameness. However, even when such methods are successfully applied, their use can still be complicated by the presence of compensatory lameness. This issue can be circumnavigated either by using diagnostic analgesia in combination with the quantitative methods[101–104] or using an additional sensor located at the withers[71]. In contrast, the methods of right/left breakover duration comparison seem to be robust to the effects of compensatory lameness. Thus, the proposed methods offer an additional benefit over the current state of the art.

5.4.4 Limitations and future work

Besides the small sample size discussed previously, this study was limited by the fact that a clinician had not been used for the initial classification of horses. Thus, lame cases had not been graded and so relationships between the severity of lameness and magnitude of asymmetries could not be comprehensively investigated. To enable discussion of possible trends which might only be seen in more grave cases, severe lameness was inferred by highlighting those horses which were out of work (SL1-3); this seemed a justified approach, in the absence of clinical gradings, as the study was a preliminary one. Another effect of not using a clinician for the initial classification is that some horses which were assigned to the sound group may in fact have been suffering some degree of lameness, as has previously been reported for owner-sound horses[72,95,309]. Therefore, future studies to investigate the points raised in this preliminary study should use lameness investigations by a clinician for the initial classification of all horses, verifying that sound horses were indeed clinically sound, and grading the severity of lameness in lame horses.

5.5 Conclusion

In conclusion, the investigated symmetry scores based on the poll and croup Acc_V were not able to differentiate between sound and lame horses, in the investigated mixed cohort of subjects, except for the most severe cases at trot. Poll motion tended to be more asymmetric compared to croup, and lower symmetry scores due to lameness were more commonly observed in the poll, especially at trot. Results of the association analysis indicated that there was no direct relationship between values of $|\overline{\Delta T_{BO}}|$ and the symmetry of the vertical upper body motion. Both approaches appeared to be capable of detecting the most severely lame horses in the cohort but upper body symmetry proved to be a less sensitive parameter than $|\overline{\Delta T_{BO}}|$ for differentiating between milder cases of lameness and sound horses. Thus, investigations on the use of $|\overline{\Delta T_{BO}}|$ to classify larger cohorts are justified.

5.6 Appendix - Details of Chapter 5 Cohort

Table 5.5 additional details of the cohort investigated in Chapter 5. age (years), height (cm), breed (ISH=Irish sports horse; Welsh C=Welsh Section C) and sex (m=mare; g=gelding) of the horses are provided as well as what the horse's main use was (where details in brackets indicate the highest level the horse competed at and BE=British Eventing). If the horse was currently in work (y=yes; n=no) is given. The lameness history, as provided by the owner, is detailed and which leg was most affected, in cases of lameness (LF=left fore; RF=right fore; LH=left hind; RH=right hind). Horses are organised into groups of sound, forelimb lame, hindlimb lame and one horse (SL3) which had severe lameness in the LF and RH. The label assigned to each horse indicates whether it was sound (S), lame but still in work (L) or one of the three so severely lame they out of work (SL).

	Horse	Age (yrs)	Height (cm)	Breed	Sex	Main use	In work	Lameness history	Most affected limb
Sound	S1	13	150	Cob	m	Dressage (Medium)	y	n/a	n/a
	S2	5	168	ISH	m	Eventing (BE100)	y	n/a	n/a
	S3	17	148	Welsh C	m	Low level schooling	y	n/a	n/a
	S4	4	178	ID	g	Low level schooling	y	n/a	n/a
	S5	6	168	ISH	g	Evening (2*)	y	n/a	n/a
	S6	4	160	Friesian	g	Low level schooling	y	n/a	n/a
	S7	4	160	Warm-blood	m	Hacking	y	n/a	n/a
Forelimb Lame	L1	14	168	ISH	g	Eventing (5*)	y	Chronic mild lameness RF; still schooling and competing at high level	RF
	L2	21	147	ISH	g	Eventing (BE100)	y	History of chronic lameness; diagnosed bilateral pedal osteitis in fore feet; most affecting RF	RF

	L3	14	174	Warm-blood	g	Low level dressage	y	Recovering from acute tendon injury to RF	RF
	L4	30	90	Shetland	g	Hacking	y	Chronic lameness due to osteoarthritis most severely affecting RF	RF
	L5	14	150	Welsh C	g	Hacking	y	Injury to knees from falling on tarmac, most affecting RF	RF
Hindlimb Lame	L6	5	166	ISH	m	Eventing (BE100)	y	Suffering acute LH lameness after sustaining injury to hock in fall	LH
	L7	14	158	ISH	m	Eventing (BE90)	y	Chronic undiagnosed lameness of RH	LH
	L8	16	168	ISH	g	Hacking	y	Arthritic changes throughout; kissing spine; presenting as RH lame	RH
	L9	16	156	ISH	m	Low level schooling	y	Kissing spine; presenting as RH lame	RH
	L10	8	166	Westfalian	m	Low level schooling	y	Presenting moderately RH lame due to pain associated with kissing spine (diagnosed)	RH
	L11	16	158	ISH	g	Low level schooling	y	History of significant chronic hindlimb lameness most affecting RH; diagnosed bilateral navicular in forelimbs; recently recovered from acute injury to LF shoulder	RH
	L12	5	168	ISH	g	Low level schooling	y	Injury to the pelvis from a fall on concrete, causing lameness in RH	RH
	VL1	18	170	ISH	g	Retired eventer (2*)	n	Chronic lameness due to arthritic changes in hocks most affecting LH	LH
	VL2	18	165	ISH	m	Retired ex-showjumper (1.60m)	n	Severe chronic lameness in all limbs; bilateral lameness in forelimbs due to flat, sore feet; significant hindlimb lameness due to tenosynovitis most prevalent in RH	RH
	VL3	14	168	Warm-blood	m	Medium dressage	n	Acute, severe, undiagnosed lameness in LF and RH	LF,RH

Chapter 6 Discussion and Conclusions

6.1 Discussion

The work carried out enabled achievement of the aim of the thesis, which was to develop tools to quantify equine gait suitable for lameness detection and assessment under field conditions. In the first study, a method for gait event detection was developed which was validated under a wider range of field conditions than any similar methods previously had been[192,194,196]. The findings of this study informed the design of the next, in which a method of lameness detection and quantification based on the investigation of the breakover duration was proposed, which would be suitable for in-field data collection. In the following sections, the three specific objectives of the thesis are discussed in more detail.

6.1.1 Propose and validate methods of gait event detection suitable for field use

Having recognised the need for methods of gait event detection which had been validated under field conditions- including on different surfaces and for varied cohorts- in Chapter 3, use of distal limb mounted IMUs was tested on a diverse group of horses at walk and trot. Comparing the timing of gait events detected using IMUs on the cannons and pasterns to reference events detected from hoof-mounted devices, it was established that novel pastern-based methods were more accurate and precise than methods which used cannon-mounted sensors[194,195,281]. Pastern-based methods were then tested on the same cohort, using data collected on two additional surfaces often encountered in the field- grass and sand. No concrete claims can be made about the accuracy of the method when applied to the additional surfaces because the reference, hoof-based method had only been validated on a hard surface. Nonetheless, results showed that the novel method agreed very well with the hoof-based when used on grass and sand.

The additional benefits of the diverse cohort (in terms of age, height, breed and use) and variety of surfaces over similar validation studies in the literature, were expected to be far reaching. Firstly, a major advantage of IMUs for gait analysis, over other systems it that they are viable under many test conditions including different surface types. Secondly, although previous methods had usually only been validated on Warmblood[194,196] or trotting[195] horses, all sorts of sizes and types of horses are used for different sports and pleasure applications. Thus, to develop methods which can easily be translated into clinical settings, for example, it is highly desirable for methods of quantitative gait analysis to be validated on representative cohorts.

Despite evident advancements provided by this study, there were nonetheless several limitations. As discussed in Chapter 4 (section 4.3.4), the most significant limitation relates to the use of the hoof-mounted IMU as a means of detecting reference gait events- a method which had been validated against a gold-standard force plate but not on the additional surfaces. However, use of the method was justified by visual inspection of the signals recorded on the additional surfaces yielding similar profiles to those on asphalt, and the fact that similar signals had previously been used to manually detect gait events from data collected on soft surfaces[174].

The novel pastern-based method, $M2_p$, has successfully been used to detect gait events in a study which developed a method of fetlock joint angle quantification using IMUs[64]. The novel cannon-based method, $M1_c$ has also been used[265] to detect gait events in a cohort of seven sound Thoroughbreds and trotters, trotting in straight lines on a hard surface. Using the hoof-based method as reference[196], they found $M1_c$ yielded slightly more accurate and precise detections of forelimb hoof-on (3(6)ms) and similar of hindlimb hoof-on (-3(22)ms) to those we had reported (-9(23)ms and -3(16)ms, respectively). For hoof-off events, lower accuracies and precisions were reported for forelimbs (-36(5)ms, compared to -15(33)ms) and hindlimbs (-45(31)ms, compared to -7(14)ms). However, it was highlighted that these high inaccuracies were likely due to differences in the definition of 'hoof-off'. Where we defined hoof-off as the moment of total lift-off, when the toe-off occurs, they defined it as the moment of heel-off, which in this thesis was called 'onset of breakover'. Thus, the methods developed in this thesis are proving similarly accurate and precise when used by other authors on additional cohorts.

In summary, the propped pastern-based methods of gait event detection using IMUs offered a substantial advancement in the literature, having been validated for a varied cohort of horses and for data collected on several surfaces. Furthermore, explorations into the methodology and application of gait event detection using IMUs meant we were well placed to tackle the next step of the thesis- in which temporal stride characteristics measured using IMUs was the focus and, hence, accurate detection of gait events was fundamental.

6.1.2 Quantify the effect of lameness on breakover duration

In the Literature Review, a paucity of publications which explored the relationship between lameness and breakover duration was identified, despite a handful of papers indicating that there may be a causal link[42,43,205,207,208]. Chapter 4 aimed to address this, quantifying fore and hindlimb breakover durations of horses at walk and trot and exploring the effect of unilateral dominant lameness on these. It was identified that, while sound horses exhibit symmetry of left/right breakover durations at walk and trot, for lame horses there is a breakdown in the symmetry, with the breakover duration of a lame limb becoming significantly longer than that of the contralateral.

Despite the discovery of this novel finding, the study had its limitations. A possibly significant limitation was that the initial classification was not carried out by a clinician. Hence, although most lame horses had received a diagnosis which was divulged to authors (see section 5.6 Appendix), the actual grade of lameness on the day of data collection was not recorded. Furthermore, sound horses were classified as such based on reports from the owner. In future studies, it would be highly beneficial for initial classification of all horses to be carried out by an experienced clinician, on the day of data collection, such that lameness can be graded, enabling investigation of the relationship between lameness severity and magnitude of $|\overline{\Delta T_{BO}}|$, (alluded to in Chapter 4). The incidence of owner-sound horses which transpire to be lame to some degree under full clinical examination[72,95,309] indicate that using a clinician to verify the state of sound horses would also be of benefit. Given the prevalence of studies which report hoof shape and shoeing to have an effect on the kinematics of breakover, it would be beneficial for such studies to also investigate the relationship between the result identified in this study and these factors. A further limitation was the sample size, despite being substantially larger than similar studies[42,43,205,207,208]. However, the results allowed sample size calculations to be conducted to inform future study design, details of which can be found in the relevant section (Chapter 4, section 4.3.1).

With the discoveries made in Chapter 4, the next logical step was to establish whether there exists a relationship between breakover duration and the upper body motion. Of particular interest was whether the asymmetries of breakover duration, found in Chapter 4 to be induced by lameness, correlated to the asymmetry in vertical head and trunk movement reported in the literature to be caused by lameness.

6.1.3 Investigate relationship between breakover duration and upper body motion symmetry with and without lameness

In the Literature Review, it was discovered that, while many publications have quantified the effect of lameness on upper body movement symmetry at trot, those which sought to understand the link during walking were far more limited[36]. Furthermore, although a handful of previous papers had inferred an effect of lameness on breakover duration[42,43,205,207,208], the relationship between breakover duration and upper body movement symmetry had not, to the authors' best knowledge, ever been investigated.

In Chapter 5, this thesis aimed to address these limitations, by first applying methods from the literature to quantify the upper body movement symmetry of a cohort of sound and lame horses at walk and trot, using IMUs attached to the poll and croup. From this, it was verified that trot was more informative of gait symmetry than walk, and the poll sensor yielded greater distinction between the movement symmetry of different horses. Next, the relationship between breakover duration at walk (using methods from the previous chapter) and upper body movement symmetry at trot was investigated in a sound and lame cohort.

This was a preliminary exploratory study and thus had significant limitations which were discussed in the chapter. Primarily, not using a clinician for the initial lameness classification, which limited the work in terms of making inferences about how the severity of lameness contributes to the alterations of gait, and the small sample size were the two most significant limitations. However, the study proved valuable for identifying several possible trends and enabling sample size calculations to inform future study designs for investigations into larger cohorts of clinically classified sound and lame horses. Furthermore, the novelty of the exploration of the relationship between breakover duration and upper body movement is expected to provide researchers in the field with new ideas for future developments.

6.2 Future Work

Having discussed the context of the findings of this thesis, in the wider setting of literature, and identified the limitations, suggestions are now made as to how future work can capitalise on the results.

6.2.1 Gait event detection in the field

While the methods of gait event detection developed in Chapter 3 were validated for field conditions not previously explored in the literature, there is scope for them to now be further tested for use in additional circumstances. As a first priority, the pastern-based methods should be validated for use on data collected from horses during circling, a common component of training and lameness workups[29]. Turning is expected to have a significant effect on the kinematics of circling[17], and hence validation specific for this exercise is warranted. Secondly, the methods should be validated for use at the additional gait of canter, which is also often used in lameness workups[29]. With these additional validation studies, it is anticipated that the pastern-based methods of gait event detection may be developed for use in even broader ranges of in-field conditions.

6.2.2 A novel tool for lameness assessment

In Chapter 4, patterns of breakover duration specific to unilateral dominant lameness were identified and it was suggested that these methods could be used in the future as a means of detecting and quantifying lameness. The next step in realising this is to test the methods on larger cohorts of sound and lame horses, where lameness has been properly assessed by a clinician and the sample sizes are chosen based on the advice in Chapter 4. A suggestion of how the results of such a validation study might be presented was described in Chapter 4 and an adaptation of the example figure is repeated here for reference (Fig 6.1). It is suggested that this figure should be recreated using a more extensive normative dataset collected from the proposed larger cohort of horses.

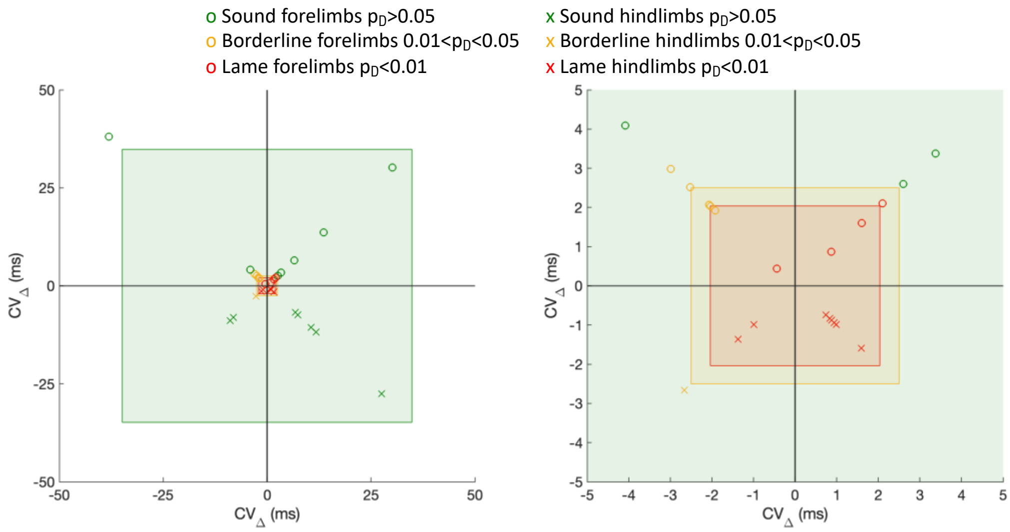


Figure 6.1 example of how the results of lameness assessment using methods developed in Chapter 4 might be presented; where green, yellow and red boxes will be used to indicate whether a limb pair is sound, borderline or lame, respectively, and the limits of boxes have been designed based on the results of the suggested larger validation study. (Adapted from Chapter 4, Fig 4.6)

With further validation and refinement, it is expected that the methods developed in Chapter 4 could form the basis of a highly informative tool for lameness detection and quantification, which may easily be incorporated into clinical settings, complimenting current subjective protocols. The tool is applied to walking data and hence should be safe for use even in cases of very severe lameness, and useable in many clinical environments, even where space is limited or the handler cannot comfortably run. Furthermore, in quantifying breakover durations, the proposed system would provide novel information compared to those currently available, the focus of which are usually upper body movement symmetry (Lameness Locator, EquiMoves, EquiGait).

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Appendix 1: Effect of Road Camber on Equine Locomotion

At its conception, the aims of this thesis focussed on the development of an IMU-based system for lameness detection and quantification using an equine treadmill. However, owing to obstacles to completion posed by the Covid-19 pandemic, inclusion of the treadmill was withdrawn, as collection of enough data was not possible within the constraints of social distancing. In a small pilot study, before data collection on the treadmill was scheduled to begin, the effect of mediolateral road camber on equine gait was investigated. In this appendix, the methodologies, results and discussion of this pilot study are presented. No significant effects of road camber on gait were discovered but the study proved invaluable as an exercise both for exploring different protocols involving equine subjects, and for developing the algorithms which were used throughout the PhD for the initial processing of data.

A1.1 Introduction

A1.1.1 Horse-Surface Interaction

For a majority of ridden and driving horses, '*hacking*' (ridden work which is undertaken outside of the menage or racetrack[1], usually for pleasure, in more open environments such as fields) is a common component of their routine. When hacking, travelling on a tarmacked public highway (*roadwork*) is inevitable for many horse and rider combinations. Traditionally, roadwork has been encouraged as a suitable method of improving the cardiovascular fitness of performance horses[2]. Meanwhile, for many hobbyist riders, roadwork is unavoidable where off-road hacking options are limited.

Extensive research has investigated the foot-surface interaction[3] and effects of different exercise surfaces on the horse. The broader aim of these has often been to understand either the risk of injury associated with different surface types[4] or the optimisation of surface properties to maximise horse performance[5]. Historically, trotting on tarmac roads was promoted as being advantageous to the development of distal limb tendons in young horses[6]. However, more recent investigations have criticised this rationale, finding that harder surfaces, such as tarmac, create higher impulsive loads, posing an increased risk of injury to the distal limb compared to softer surfaces such as sand or turf. It has been reported that trotting on tarmac roads produced shocks (peak decelerations) of up to 10 times greater than those seen when the horse was trotted on sand, wood fibre or wood chip and up to 20 times greater than those recorded on grass or a well-maintained arena surface[7]. In 2018, a study investigated forelimb foot placement, hoof vibration and movement symmetry in pleasure horses on three common hacking surfaces- tarmac, grass turf and sand[8]. IMUs mounted on the poll, croup and both tuber coxae and an accelerometer on one hoof, with a high-speed video camera to record foot placement, were used to characterise equine gait. It was found that perceived surface firmness had a significant effect on the vibration power and frequency parameters of hoof-impact and that vibration power parameters were significantly greater at trot than walk. The same was not true for vibration frequency.

Despite these investigations into the effect of road-like surfaces on horses, to the best knowledge of the author, no previous research has sought to investigate the effects of road camber on equine locomotion. Previously, the effect of mediolateral gradients on equine gait has, however, been investigated in a different context. There have been several investigations into the correct degree of banking of racetracks[9–12].

In racehorses, authors describe how this factor can be used to significantly influence the angles and magnitudes of loading on equine athletes, assisting them in reaching maximal speeds[13]. Articles which investigated banking of racetracks highlighted that horses are able to adaptively respond to changes in surface, adjusting their gait and posture to reduce loading and achieve greater comfort[13]. A paper which investigated the effect of track banking on Standardbred horses pulling a sulky (small racing trap), claimed that this case was more comparable to a vehicle moving on banked track, compared to a ridden racehorse, as the sulky would restrict sideways movement of the horse. This article cited that biological systems are able to adapt both in the long term- with evolutionary changes- and in the short term- with local structural changes or rapid adaptations of gait- to reduce stresses. The results of these investigations into the effect of mediolateral inclines are not directly applicable to the scenario of road camber as they were addressing gradients only on turns and not straight lines; did not investigate motion on tarmac; and were addressing speeds much higher than those commonly reached when roads are used for fitness work or pleasure riding.

With previous studies having found the mediolateral incline of racetracks to have a significant effect on equine gait, it is hypothesised that the mediolateral incline of road camber will also have a significant effect on equine locomotion. With reference to the above findings, it is suggested that horses may exhibit adapted gait patterns in response to camber. Furthermore, horses which are regularly exercised on cambered roads may have localised changes in structure as a result, although this suggestion goes beyond the scope of the study.

A1.1.2 Definition of Camber

Road camber refers to the mediolateral slope applied to roads during tarmac laying to both ensure effective drainage of water away from the road and to assist road vehicles in cornering safely[14]. There are three common camber profiles: parabolic (reaching a peak at the crown of the road and falling away parabolically to the kerbs), sloped (reaching an apex at the crown of the road and falling away to the kerbs linearly) and composite which can be a combination of the two profiles. In some cases, roads are laid with super elevation meaning the road slopes linearly across both carriageways up towards the outer edge of a corner. The camber is chosen depending on the conditions and requirements at the specific location.

Government guidelines stipulate that a mediolateral gradient of 1:30 provides sufficient drainage in most cases[15] but cambers as steep as 1:20 are possible[16].

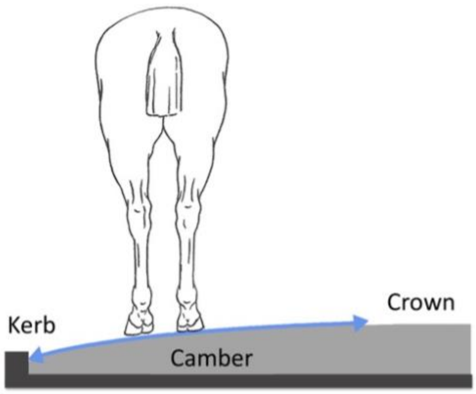

Figure A1.1 schematic of a horse, on a parabolic camber, on the left-hand side of the road as is legally required in the UK

Several hypothesises were to be tested in this study. Firstly, that horses will adapt their gait in response to camber. Particularly, that the stance durations of all the limbs would become longer on camber compared to a flat surface as the horse attempts to increase its stability on the uneven surface. In the UK, horses must be ridden on the roadside near to the left-hand kerb (Fig A1.1)[17]. Hence, secondly, it was suggested that the stance duration of the right limbs on camber, which would be on the more elevated section of road, would be longer than those of the left limbs on the same surface and of the same limbs on the flat surface. Furthermore, it was suggested that the asymmetric nature of the cambered surface would induce asymmetries of gait similar to lameness and that gait would become more irregular on camber.

Investigation of these hypothesises would enable the full risk and potential benefits of roadwork to be properly understood, and informed decisions made when planning exercise routines. Kinematic gait analysis techniques were used to compare gait on a hard, flat surface and cambered road. Results offer a first indication as to whether differences exist between equine gait in the two conditions.

A1.1.3 Aim and Objectives

Hence, the aim of this study was to investigate the effect of mediolateral road camber on equine locomotion. To achieve this, horses would be recorded, using gait analysis equipment, being ridden on a hard flat surface and a cambered tarmac road at walk and trot. To test the outlined hypothesises, data processing techniques would be used to calculate temporal stride parameters and symmetry indices and, from these, deduce whether the introduction of camber affects equine gait. From these results, it was to be inferred whether long term and regular use of roadwork is likely to increase the risk of injury to the horse.

A1.2 Materials and Methods

A1.2.1 Subjects

Nine riding horses with a mean age of 10(4.5) years and height of 157(12) cm were used in this study. All horses and their riders satisfied the inclusion criteria (Table A1.1). Horses were ridden by riders who they were accustomed to, with six different riders recruited in total. Ethical approval was granted by The University of Sheffield Research Ethics Department and informed consent was collected from each of the participating riders and horse owners.

Table A1.1 inclusion criteria for horses and riders

Rider	**Horse**
Aged 17-60 years	Aged 4-20 years
Normally fit and healthy	Normally fit and healthy
Able to maintain 5 minutes of working trot rising without observable fatigue	Able to maintain 5 minutes of working trot rising without observable fatigue
5+ years of riding experience	Roadwork included regularly in training regime
Sufficient experience of roadwork	Comfortable with level of roadwork required

The horses selected were of various different breeds and types. They were also used for a range of different purposes; some were leisure horses used mainly for recreational riding while others were high level sports horses. Such a varied cohort was selected in the hope that it would be representative of the wide range of horses that undertake roadwork. Some horses were shod and others were not. It has previously been reported that this variable can have a significant effect on hoof-surface interactions and, hence, can significantly affect gait[18]. However, this study intended to yield results which would be relevant both to shod and unshod horses. Therefore, the date of the last shoeing or hoof trim prior to data collection was recorded but the variable was not controlled.

A1.2.2 Data Acquisition

Data was collected using a system of six Shimmer3 IMUs. Two sensors were placed at midline locations and four at the limbs (Fig A1.2). Sensors were attached at the level of the third meta-carpal and -tarsal bones (*cannons*) on the right and left limbs; and at the poll and croup. All sensors were monitored throughout data collection to ensure they had not moved significantly or become loose.

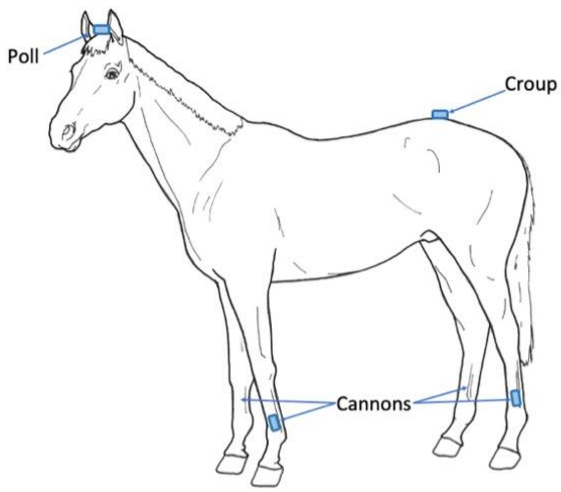

Figure A1.2 schematic of sensor placement on horse

The IMUs recorded data at a 100Hz sampling frequency. Accelerometers were set to a range of ±16g at the upper body and 200g at the limbs; gyroscopes recorded ranges of ±2000deg/s and magnetometers ranges of ±49Ga.

A1.2.3 Protocol

Throughout all trials, horses were ridden by their usual rider. The horse's usual tack was worn, including a bitted bridle and saddle. A 50m recording area was laid out using cones as per Fig A1.3. Horses first halted at cone 1 for several seconds before moving off. They were then walked or trotted from cone 1 to cone 4. At cone 4, they were asked to halt again for several seconds. The horse accelerated from halt to steady gait in the first 5m, between cones 1 and 2, and decelerated in the last 5m, from cone 4 to 5, from steady gait back to halt. The 5m distance was deemed sufficient to allow the acceleration and deceleration. The sequence was repeated until five walk and five trot trials were correctly recorded. The time instance when the horse passed cones 2 and 3 were recorded by a time-synchronised input given to the system such that the central 50m of data, where the gait was expected to be steady, could be isolated retrospectively.

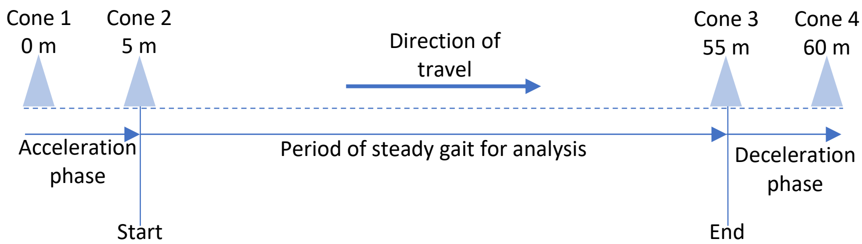

Figure A1.3 schematic of trial recording area

The entire protocol was carried out separately on a flat, hard surface and on a cambered, tarmac road. Both trial areas were chosen such that data could be recorded in a straight-line and with a negligible gradient in the direction of the horse's travel. The cambered trials were conducted on roads where the kerbside elevation was lowest, as per Fig A1.1. Whether the flat or cambered road data was collected first was random. Throughout trials, the rider was asked to encourage the horse to maintain walk or trot using usual voice and leg aids, but the exact speed of the gait was self-selected by the horse. Whether the rider carried a riding crop was left to their own discretion.

A1.2.4 Data processing

For the purpose of these analyses, only the central 50m of the pass, where the horse was expected to have maintained steady gait, were used. Methods developed in a previous section ($M1_C$, Chapter 3) were used to detect the hoof-on and -off gait events from each of the four cannon-mounted sensors using the acceleration data.

A1.2.4.1 Average speed and stride durations

Firstly, the average speed (v) of each trial was calculated (Eq A1.1) from the trial duration (td) and length of the test run (50m), to understand whether the difference in surfaces had an effect on the overall speed of the horse.

$$v = \frac{50}{td} \quad (A1.1)$$

In the previous chapter, forelimb hoof-on events had been the most accurately and reliably detected type of gait event. Hence, in this chapter, hoof-on events from the left forelimb (*LFon*) were used to calculate the stride durations (T) according to Eq A1.2.

$$T = LFon_{n+1} - LFon_n \quad (A1.2)$$

A1.2.4.2 Stance and step durations

To investigate the hypothesised effects of camber on stance duration, the detected gait events were used to calculate the stance durations of each limb, calculated as per the definitions in a previous chapter (Eq A1.2).

To understand whether the introduction of camber had an effect on the overall gait pattern, the temporal parameters of each limb relative to the others had to be investigated. For this, the step durations were calculated, (as in Chapter 1) and compared between flat and cambered conditions. Steps were defined as the time duration between subsequent hoof-on events of different limb pairs. Stance and step durations were calculated as percentages of total stride duration. This allowed easier comparison at the group level, with the wide variation in cohort meaning that some horses naturally had longer or shorter stride cycles than others.

All stance and step durations were calculated for each horse. The mean and standard deviations for each of the four conditions (walk on flat, walk on camber, trot on flat and trot on camber) were then obtained for every horse.

A1.2.4.3 Autocorrelation

It has previously been explained how the autocorrelation of data recorded along the midline of the horse can be used to quantify gait symmetry and regularity. It was hypothesised that the asymmetric nature of the cambered surface would induce asymmetries of gait in the horse, similar to those observed in cases of lameness. Furthermore, it was suggested that the camber would cause a decrease in the gait regularity as the horse would be less sure of its footing. To test these hypotheses, previously described autocorrelation techniques were applied to the vertical acceleration signals from the poll and croup. This analysis was carried out on the first ten strides of each trial, taken from the first to the eleventh hoof-on event of the left forelimb. Signals were rotated into a vertical-horizontal frame using methods developed by Moe-Nilssen[19]. The autocorrelation coefficients of the vertical acceleration of the poll and croup were used to indicate the gait symmetry and regularity in the cranial and caudal ends of the horse, respectively.

A1.2.4.4 Statistical analysis

For all parameters, statistical analysis was conducted at the group level. First, datasets were tested for normality using a Shapiro-Wilks test for normality. Those datasets which satisfied the normality test were then tested for significant difference using a paired Student's t-test. Datasets which were not normally distributed were tested for significant difference using a Wilcoxon Signed Rank test. A significance cut off value of p = 0.01 was chosen for each level of analysis owing to the small sample size.

A1.3 Results

A total of 1310 and 1344 walk strides on flat and cambered surfaces, respectively, and 935 and 1002 trot strides on flat and cambered surfaces, respectively, were analysed.

A1.3.1 Average Speed and Stride Duration

The average speed and stride duration for each horse in the flat and cambered surface conditions at walk and trot are shown subsequently as boxplots (Figure A1.4).

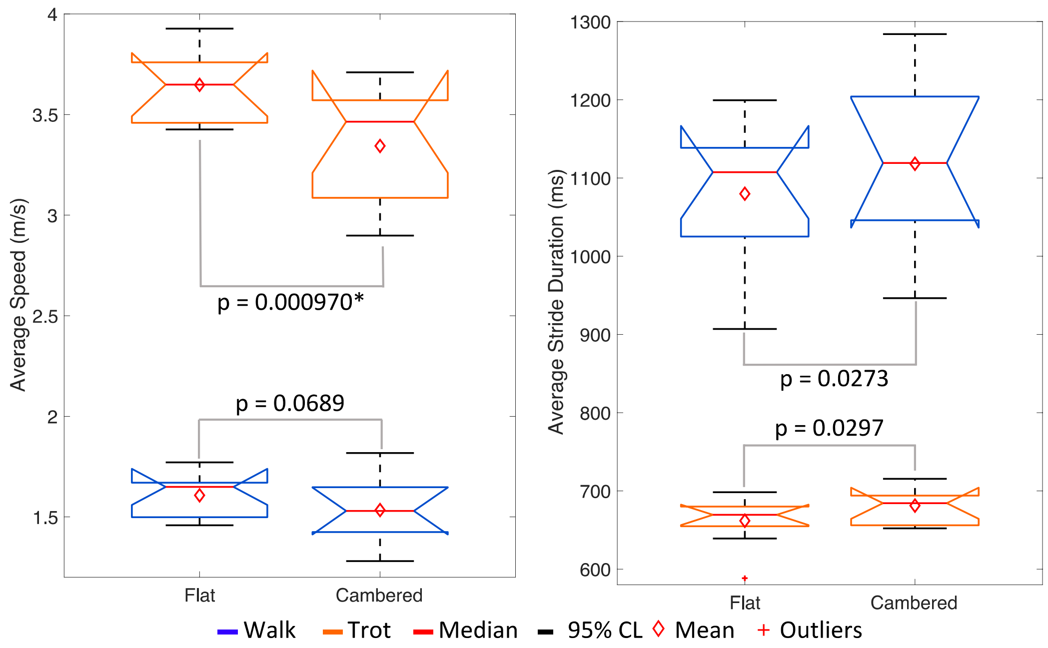

Figure A1.4 boxplots of average trial speeds and average stride durations, under flat and cambered surface conditions, for walk (blue) and trot (orange). The mean values are shown as red diamonds (◊). Red lines are the median values. Whiskers represent the 95% confidence limits (CL) of all points not considered outliers and outliers are shown as red pluses (+). The p-value results of paired Student's t-test are shown

At both walk and trot, the introduction of camber had the effect of slowing horses down, overall, and increasing the stride duration but only the difference in average trot speeds was significant. Absolute differences in speed were greater for trot than walk and absolute differences in stride duration were greater for walk than trot.

Table A1.2 mean gait speeds, mean stride durations and standard deviations (in parenthesise) for walk and trot trials recorded on both surfaces. P-values are the results of a paired Student's t-test.

		Flat	Cambered	Difference	Difference (%)	t-test
Speed (m/s)	Walk	1.61 (0.12)	1.53 (0.17)	-0.08	-5	0.0689
	Trot	3.65 (0.26)	3.46 (0.34)	-0.19	-5	0.000970*
Stride (ms)	Walk	1072 (99)	1110 (124)	35	4	0.0273
	Trot	660 (41)	679 (38)	9	3	0.0297

The Shapiro-Wilks test for normality revealed that both the average speeds and average stride durations data were normally distributed. Hence, a paired Student's t-test was used to check for significant differences in the means of each. Camber had the effect of reducing the average walk speed by 0.08m/s and the average trot speed significantly by 0.19m/s. For both gaits, this was a speed reduction of 5%. Camber also appears to have increased stride duration by 38ms at walk and 19ms at trot. These were increases of 4% and 3%, respectively and were not significant differences, with p-values greater than the 0.01 cut off.

A1.3.2 Stance and Step Durations

The group-level results of stance and step durations calculated using previously developed methods, for walk and trot recorded on both surface types, are displayed in Table A1.3.

Table A1.3 table of mean (average values at the group level) and standard deviation of the mean; and variability (mean value of the standard deviations from each horse) and standard deviation of the variability of each limb at walk and trot on flat and cambered surfaces. The p-value results of a Wilcoxon signed rank statistical test for significance.

		FLAT		CAMBERED		SIGNED RANK
		mean	variability	mean	variability	p-value
WALK						
Stance (ms)	Left fore	63(3)	6(2)	63(3)	8(3)	0.945
	Right fore	64(3)	5(2)	66(2)	5(1)	0.0391
	Left hind	62(3)	7(1)	59(4)	7(1)	0.0781
	Right hind	62(4)	6(1)	61(4)	7(2)	0.461
Step (ms)	Left	71(2)	5(3)	71(4)	10(3)	0.641
	Right	74(3)	6(3)	74(6)	7(5)	0.945
	Front	47(3)	4(2)	48(2)	6(4)	0.461
	Back	50(1)	4(2)	49(3)	5(4)	0.148
	Left diagonal	75(2)	6(2)	74(4)	5(2)	0.250
	Right diagonal	77(2)	6(4)	74(4)	10(7)	0.195
TROT						
Stance (ms)	Left fore	59(11)	3(2)	59(11)	3(1)	1.00
	Right fore	58(11)	3(1)	60(11)	3(1)	0.0156
	Left hind	58(12)	4(2)	57(12)	4(5)	0.742
	Right hind	58(12)	3(1)	58(11)	4(3)	0.641
Step (ms)	Left	37(20)	3(2)	36(20)	2(0)	0.195
	Right	40(11)	2(1)	40(10)	2(1)	0.945
	Front	48(11)	2(1)	48(11)	3(1)	0.383
	Back	51(2)	3(2)	51(1)	2(1)	0.250
	Left diagonal	24(25)	3(3)	23(25)	4(5)	0.547
	Right diagonal	25(16)	2(1)	25(16)	2(0)	0.547

The Shapiro-Wilks test revealed that these data were not normally distributed. Hence, a Wilcoxon signed rank test was used to check for significance. No significant differences were seen, between surfaces, for any parameters. For the stance durations, no differences were found either on an intra-limb basis between the two surfaces nor between different limbs when comparing on an inter-limb basis. The mean stance durations were the same for all limbs at each gait and under each condition. This average stance duration was 63% at walk and 58% at trot.

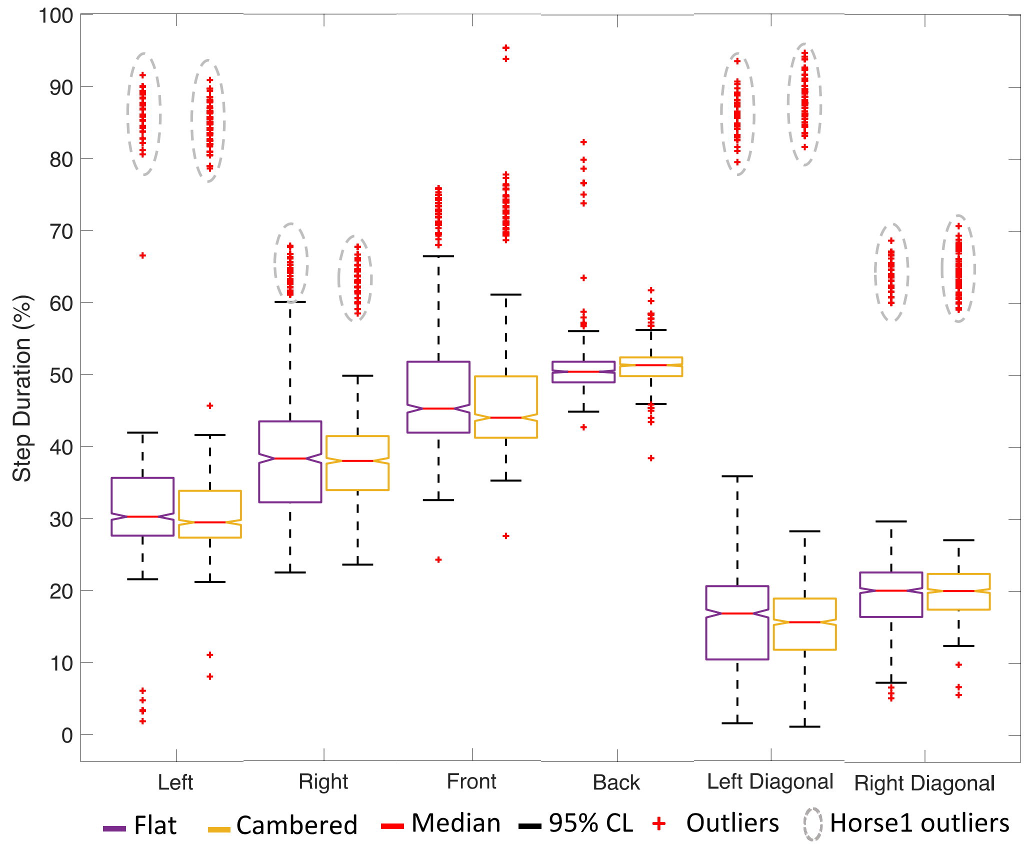

Figure A1.5 boxplots derived from every step duration as a percentage of total stride duration calculated from each horse at trot under flat (purple) and cambered (yellow) conditions. Red lines indicate median values of relative step duration, box limits represent the 95% confidence limits (CL), whiskers indicate the most extreme values not considered outliers. Outliers are represented as red pluses (+). Dashed grey circles indicate outliers attributable to horse1.

Neither the mean nor the distribution of the values of relative step duration changed between surfaces for either gait. For the step durations at trot, the standard deviation of the mean values seemed quite high, ranging from 2 to 25% compared to a range of 1 to 4% for walk. Yet, the variability and standard deviation of the variability were low and comparable to those for walk. This indicated that there was high variation in the values at the group level but not at the individual level. To better understand this, all the trot steps from each horse were investigated, in addition to the mean values (Fig A1.5). For the ipsilateral and diagonal limb pairs, all the extreme outliers were found to be attributable to a single horse- horse1. These are highlighted in Figure 5.2 by grey dashed circles. The standard deviation of the variability being low for all parameters, ranging from 0 to 7% and having an average value of 2%, indicates that all horses exhibited the same degree of consistency in stance and step durations for all conditions.

A1.3.3 Autocorrelation

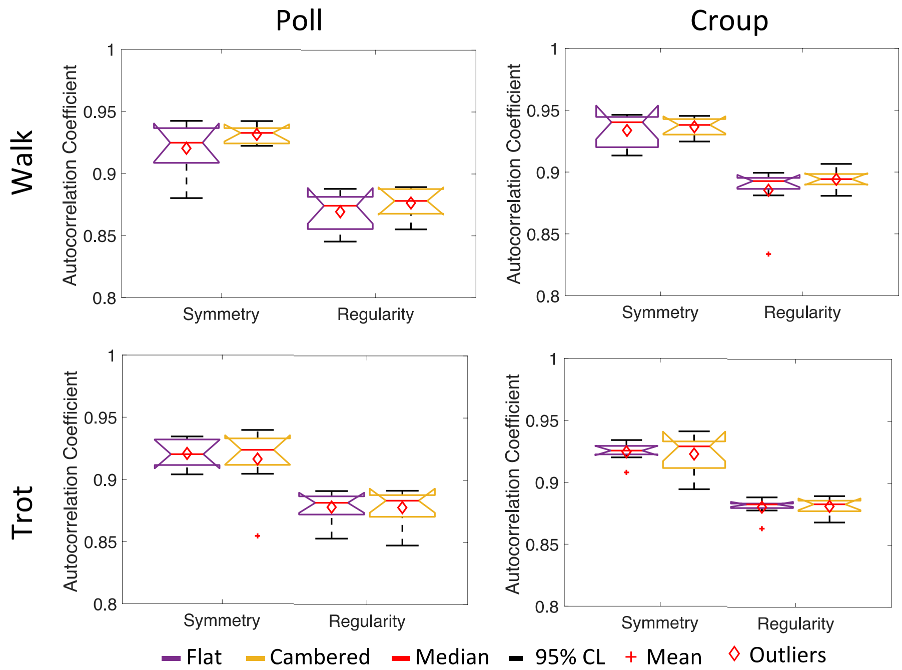

Figure A1.6 boxplots derived from every step duration as a percentage of total stride duration calculated from each horse at trot under flat (purple) and cambered (yellow) conditions. Red lines indicate median values of relative step duration, box limits represent the 95% confidence limits (CL), whiskers indicate the most extreme values not considered outliers. Outliers are represented as red pluses (+). Dashed grey circles indicate outliers attributable to horse1.

According to the results of the autocorrelation, the movement symmetry and regularity of fore and hindquaters did not alter with surface type. The results of the Wilcoxon-Signed rank test confirmed that no significant differences existed between mean values calculated on each surface.

A1.4 Discussion

A1.4.1 Average speed and stride duration

The results of average speed at the group-level suggest that the introduction of camber tends to cause an overall slowing down of the horse's gait at both walk and trot, but this change was statistically significant only for the latter. It has previously been reported that a horse will slow its gait to increase stability when moving on unfamiliar surfaces, for instance a treadmill[20]. Therefore, it is suggested that the horse tended to move more slowly on a cambered surface compared to a similar flat surface, in order to be sure of foot placement.

Although results suggested that the average speed was slower on camber compared to flat surfaces, the actual reduction was of only 5% at each gait and hence only marginal.

Studies which investigated the effect of gait speed on the physiological cost of exercise, in fact, consider speed differences of less than 10% as being not of importance[21]. However, the information that the horse will move slower on cambered surface could be of relevance for the riders, who can make an informed judgement as to how to react. If the roadwork is to increase cardiovascular fitness, the rider may choose to encourage it faster on cambered road, to match speeds reached without intervention on flat surfaces, in an effort to match the physiological demands. Conversely, the rider may decide that the horse lacks sufficient balance or soundness to move faster on the cambered surface and, hence, that it would be unsafe or unethical to push them faster. In this case, the rider may choose to support the horse to adopt the more conservative speed by, for instance, slowing their rising down at trot.

The decrease in speed was as a result of an increase in stride duration on cambered surface, at both walk and trot, compared to flat surface. The increases in stride duration were in fact 4% for walk and 3% for trot but these differences were not statistically significant. The stride durations were calculated using gait events determined using the method developed in the previous chapter. This method claims to detect walk and trot hoof-on events with a greater error than 3% and 2% of stride cycle, respectively. Considering these two points, it cannot be claimed that the stride duration changed between surfaces.

A1.4.2 Stance and Step Durations

The mean stance durations did not vary between surfaces for any limb in either gait. Any apparent differences were smaller than the accuracy with which the algorithm developed in the previous section is able to detect gait events. These results indicate that the hypotheses which suggested all relative stance durations would increase on camber compared to flat and that right limb stance durations would be longer on camber compared to left limbs, ought to be rejected.

In trot, the stance durations appear to have varied more on the group level than at the individual level as the standard deviation of the mean is markedly higher than the standard deviation of variability, for each limb. This suggests that there was much more variation between different horses compared to between trials of the same horse. This could be explained by the widely varied cohort that was chosen, with different breeds having naturally different gaits.

The steps (duration between hoof -on events of limb pairs, as per Chapter I), were calculated and analysed to understand how the limbs behaved relative to each other and, hence, characterise the gait at the system level. No differences were seen between the steps recorded on the flat and cambered surfaces for either walk or trot. As with stance durations, any small differences which were seen in step durations were smaller than the error incurred by the gait event detection algorithm. At walk, the relative duration of the left and right, front and back, and left and right diagonal steps are expected to be equal[22]. The results of this study conform to this assumption. From this, it can be concluded that these horses all walked using the conventional pattern of footfall.

The standard deviations of mean values of step duration at trot appeared to be very high, indicating a lot of variation at the group level. However, the variability values were not high, this suggested that the within-horse values of standard deviation were not notably high. To better understand this feature, the step durations for individual horses were considered. The results of this are presented as boxplots in

Fig 3.5. The outliers highlighted in Fig 3.5 by the green circles are all attributable to horse1. On both surfaces, this horse displayed a mean Left Step duration of 85%, Right Step of 65%, Left Diagonal of 85% and Right Diagonal of 65%. These values were much higher than the same step durations observed for the other horses. The front and back step durations for horse1 were not different from the rest of the group.

The aim of most training formats, particularly Western dressage, is to encourage the horse to carry more weight on the hindlimbs and generate power from the hindquarters. Hence, trained horses develop a trotting gait pattern in which the diagonal limb pairs either hit the ground at the same instance in time or the initial contact of the hindlimb of the diagonal limb pair leads that of the forelimb. In this context, the interpretation of the above phenomena is that horse1 adopts a trot gait pattern in which the forelimb of the diagonal limb pair lands before the hindlimb.

It has sometimes been reported that lameness can cause the forelimbs to land earlier than the hindlimbs, in a similar pattern[23]. However, authors suggest that the pattern seen for horse1 is likely due to the horse's conformation and training as a driving horse. Therefore, it is suggested that horse1 habitually adopts a hindlimb-first gait pattern for this reason. Further studies are needed to investigate generalisability of this hypothesis.

A1.4.3 Autocorrelation

In this study it was suggested that the asymmetric cambered surface would induce an asymmetric gait in the horse and that the gait regularity would also be reduced. Autocorrelation methods we used, as described in a previous section, to quantify the gait symmetry and regularity at the fore and hind end using the vertical poll and croup accelerations, respectively. The results of this analysis did not differ between surfaces, with boxplots overlapping considerably and the p-values being very high, indicating insignificantly different means in all cases.

In the case of walk, symmetry and regularity actually appeared to increase, very slightly and the range decrease, on camber compared to flat. These differences were, however, not statistically significant. These results suggest that the hypothesis that gait symmetry and regularity would be lower on a cambered surface than flat, ought to be rejected. The sum of the symmetry and regularity indices has previously been suggested to offer a measure of gait stability. Therefore, if the symmetry and regularity indices do not alter from one surface to the other, this suggests that gait stability remained unchanged, too.

It was previously cited that horses are known to slow the overall gait pattern to increase stability. The unchanged symmetry and regularity presented in this study suggest that, by slowing their gait by an average 5%, the horses are effectively maintaining the same level of gait stability when they walk and trot on the cambered surface. In future work, it may be advantageous to investigate whether symmetry, regularity and, hence, stability are affected if the horse is encouraged to walk and trot on camber at speeds which match those on the flat surface. This may also give more information as to whether it is safe to encourage the horse faster on camber.

A1.5 Conclusion

In conclusion, the average speed of horses tended to decrease by a mean value of 5% when walking or trotting on the cambered road compared to flat surface. This is something that the rider may wish to consider and influence their horse according to the intended purpose of the roadwork and ability and soundness of the individual horse. Relative stance and step durations did not change between conditions, suggesting that the only difference was an overall slowing down of the entire gait pattern. Symmetry and regularity were unchanged in all conditions indicating that the slowing was an effective strategy to maintain gait stability. These findings suggest that exercising horses on cambered road does not pose any greater risk than those incurred on flat tarmac road.

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