An investigation into the efficacy of kinematics and kinetics method for stride-characteristic measurements of horses trotting on a treadmill

Beatrice Bathe (2014)

An investigation into the efficacy of kinematics and kinetics of the sternum as a method for stride-characteristic measurements of horses trotting on a treadmill

Beatrice A. M. Bathe

A thesis submitted in partial fulfillment of the requirements of Oxford Brookes University for the degree of Master of Philosophy.

Undertaken in collaboration with Hartpury College, Gloucester.

August 2014

Abstract

The aim of this study was to investigate the validity of stride characteristic measurements taken from the *sternum* by means of an Optical Motion Capture System (OMCS) and an Inertia Measurement Unit (IMU), in comparison with OMCS hoof markers. Measurements were taken from sound horses of a range of breeds, trotting at self-selected speeds on a treadmill (OMCS N=15; IMU N=4). Hoof marker trajectories were compared in terms of dorsoventral position (*p*Z), craniocaudal velocity (*v*X) and dorsoventral velocity (*v*Z). Contra-laterally coupled limbs were compared at beginning and end of stance according to *v*X. A Girth Marker (GM) placed over the *sternum* was used to identify beginning and end of stance of each diagonal using dorsoventral acceleration (*a*Z) and dorsoventral velocity (*v*Z) respectively. These were compared with hoof marker *v*X. GM *a*Z and *v*Z were then validated against the same measurements taken by an IMU measuring at the same time from the same location.

No significant difference ($p < 0.05$) was found by ANOVA between hoof marker trajectories *p*Z, *v*X or *v*Z at beginning or end of stance. No significant difference was found by t-test or ICC between contralaterally coupled limbs at beginning or end of stance. GM *a*Z and *v*Z could be used to identify beginning and end of stance for each diagonal without significant difference from hoof *v*X timings according to t-test and ICC. OMCS GM and IMU did not differ in terms of velocity (peak or trough timing or amplitude, or absolute difference: peak minus trough), or acceleration peak timing, trough timing or trough amplitude according to t-test or ICC. However, OMCS GM and IMU differed significantly in terms of acceleration peak amplitude ($p = .01$, ICC = 0.46) and absolute difference ($p = .04$, ICC = 0.66).

The *sternum* can be used as a site to collect data providing accurate information on beginning or end of stance of horses with no advanced placement of contralaterally coupled limbs, whilst trotting at self selected speeds on a treadmill. Temporal acceleration data, and temporal or amplitudal velocity data are sufficient to identify beginning and end of stance from the *sternum* using an IMU. Amplitudal acceleration data from an IMU should be further investigated before assumed valid under these conditions.

Acknowledgements

This work was carried out by the Movement Science Group (MSG) at Oxford Brookes University in collaboration with the Equine Therapy Centre at Hartpury College, Gloucester.

I would first like to thank the MSG, most particularly Ken Howells. Without Ken's patience, expertise and diligence this study could not even have been attempted. I am also grateful to Helen Dawes, Johnny Collet, and Patrick Esser for their supervision and support throughout this process. My supervisors have not only been academic mentors, but they and the MSG have become personal friends with whom I hope to always keep contact.

I am grateful to Kathryn Nankervis of Hartpury College, not only for supplying subjects and facilities for testing, but also for academic guidance and for her infectious enthusiasm.

I would like to thank my family for their unconditional confidence in me: my grandparents who have forgotten more than I'll ever know; my parents who always find a reason and a way to support me; and my siblings who laugh me away from the edge of peril.

Finally I would like to thank Jason, the bravest man alive: who knows the worst of me and still remains.

This thesis is dedicated to Peggy:

An inspiration in every way.

Abbreviations

2D	Two Dimensional
3D	Three Dimensional
a	acceleration
AAEP	American Association of Equine Practitioners
ANOVA	Analysis of Variance
CI	Confidence Interval
cm	centimetres
CoM	Centre of Mass
g	grams
GM	Girth Marker
GPS	Global Positioning System
GRF	Ground Reaction Force
HL	Hind Left
HR	Hind Right
Hz	Hertz
ICC	Intraclass Correlation Coefficient
IMU	Inertia Measurement Unit
κ	Kappa value
kg	kilogram
LF	Left Fore
LLoA	Lower Limits of Agreement
LoA	Limits of Agreement
m	metres

mm	millimetres
m/s	metres per second
N	Newton
OMCS	Optical Motion Capture System
p	position
QTM	Qualisys Track Manager
RF	Right Fore
s	seconds
SD	Standard Deviation
UK	United Kingdom
ULoA	Upper Limits of Agreement
v	velocity
<u>X</u>	in the craniocaudal plane
<u>Y</u>	in the mediolateral plane
<u>Z</u>	in the dorsoventral plane

Glossary

Advanced limb placement

Or diagonal advanced placement is a feature of some trots where dissociation is found between diagonally coupled limbs at either beginning or end of stance. If the value is positive then the hindlimb acts before the forelimb, and vice versa.

Bridle

The headgear used as an aid for direction of the horse, consisting usually of a metal 'bit' in the mouth.

Cannon

Metacarpal III (fore) or *Metatarsal III* (hind)

Coffin joint

Interphalangeal joint

Collected trot

A short striding trot in a compressed outline, without losing impulsion.

Elbow

Radiohumeral joint

Fetlock

The *metocarpophalangeal* joint (fore) or *metatarsophalangeal* joint (hind)

Girth

A strap that runs under the abdomen of a horse to prevent a saddle slipping.

Hock

Also known as the tarsus, the tarsal joint between *Tibia* and *Metatarsal III* (hind cannon)

Hip

Coxofemoral joint

Knee

Also known as the carpus, the carpal joint between *Radius* and *Metacarpal III* (fore cannon)

Lameness

'*An abnormal stance or gait caused by either a structural or a functional disorder of the locomotor system, caused by trauma, congenital or acquired disorders, infection, metabolic disorders, and nervous and circulatory system disease'* (Adams, 2012)

Left-handed racecourse

Requiring the horses to run counter-clockwise.

Passage

An advanced dressage movement in which the trots forwards in a highly elevated and collected manner.

Pastern

Phalanx I

Piaffe

An advanced dressage movement in which the horse trots in a slow elevated manner (almost) on the spot (with neither backwards nor forwards movement).

Poll

External occipital protuberance

Soundness

Absence of lameness.

Stifle

Joint of *Femur* and *Tibia*

Surcingle

A wide strap that runs around the abdomen of a horse, used to keep a blanket or other equipment in place.

Withers

Spinous processes of thoracic vertebrae 3-5

Working trot

The most natural of the trots under saddle, most similar to self selected in hand trot.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Equine Gait Assessment

The description and detection of gait normalities and abnormalities are of great significance to the horse industry. Knowledge of gait may aid the prediction of a young horse's athletic potential, the suitability of breeding programs, any predisposition to lameness, its treatment and monitoring, as well as training monitoring of horse and rider.

The significance of assessor experience is well documented in equine gait analysis (e.g. McCracken *et al.*, 2012. See section **1.3.2**) it therefore seems likely that horses bred or bought by experienced breeders, trainers and dealers are likely to display fewer gait faults than animals belonging to a less experienced owner who is purchasing or breeding a riding horse as a pet, rather than investing in competition potential. Further, different breeds and pedigrees have been established that predispose the skeletal structure to different shapes, and thus the animal to specific disciplines, gaits and gait qualities. However, the research into gait focuses predominately on elite (or potentially elite) horses due perhaps to the ease of access to numbers in large yards, breed standardisation, and funding available at this level. Therefore the results may not be applicable to average riding horses.

Gait analysis is most regularly performed by means of the horse being led at a forward, free flowing pace in a straight line at both walk and trot (with an option for circling, reversing and ridden work).

The trot is a naturally occurring gait at which the limbs move in diagonal pairs (right fore and hind left – suspension – left fore and hind right – suspension). The self-selected trot has demonstrated impressively low intra-individual variation in terms of speed (coefficient of the mean 6.2%), stride duration (1.8%), stride length (4.2%), and average joint angles (elbow, carpus, front fetlock, front coffin, hip, stifle, tarsus, hind fetlock, hind coffin) (4.7%) (Degueurce *et al*., 1997).

The Merck Veterinary Manual defines lameness (without reference to symmetry) as *'an abnormal stance or gait caused by either a structural or a functional disorder of the locomotor system, caused by trauma, congenital or acquired disorders, infection, metabolic disorders, and nervous and circulatory system disease'* (Adams, 2012).

Laterality is well documented to a varying degree in different breeds of sound horses, with Thoroughbreds demonstrating left leg dominance in 40.5% of trials, ambidexterity in 50% of trials, and right leg dominance in only 9.5% of trials (McGreevy *et al.*, 2006). This is of little hindrance to their potential as the majority of British racecourses run left-handed. The same study found a much greater degree of symmetry in Quarter Horses, with only 10% left leg dominance, 82% ambidexterity and 7.5% right leg dominance. Dressage is perhaps the British equestrian sport requiring the greatest degree of symmetry and ambidexterity – this is most likely bred as well as trained into the animals: no leg preference was found in 16 Fédération Equestre Internationale and Grand Prix dressage horses by Argue *et al*., (1993) in walk trot transitions.

Conversely, symmetrical horses can be lame, as was proved in a study by Buchner *et al.* (1995) that induced 11 sound horses with mild bilateral lameness by applying pressure to the soles of their feet. The horses trotted at an enforced speed on a treadmill showed no asymmetry, nor decreased stride length or stance time according to kinematic objective measurements. But in advanced hind limb placement, forelimb placement occurred significantly earlier, and maximal hyperextension of the forelimb significantly decreased. The authors concluded that unless the horse was first analysed when sound, the presence of a mild bilateral lameness would be hard to detect due to the enduring symmetry.

Although lameness is neither synonymous with asymmetry nor antonymous with symmetry, the trot is often considered the most useful gait for subjective analysis of sports and riding horses (with the exception of racehorses), as a broadly symmetrical gait (unlike the canter or gallop) many cases of lameness or asymmetry are most evident in the trot.

1.2 The Prevalence of lameness

The absolute requirement of the horse to retain its locomotory capabilities is summarized in the old adage ‘no foot, no horse’ (Bridges, 1751). There remains a sizable prevalence of lameness in equine athletes; one study found that in two-year-old flat racehorses 22% of training days were lost to lameness, and of all the days lost from training 82% of these were due to lameness (Dyson *et al.*, 2008).

This is not unique to racing; in one study of 765 horses being trained for a Concours Complet International three-day event 21% failed to attend due to injury, of these at least 70% manifested as lameness or gait abnormality. Up to a 28% more may also have shown similar symptoms but were categorized only as 'undiagnosed lameness/illness' (Singer *et al.*, 2008).

The physiological effects of stress on equine injury are also beginning to be investigated. Wagner (2010) described the recovery inhibition, as well as the analgesic effect caused by stress that can mask the extent of injury; failure to detect the early signs of lameness and continuing to work the animal could cause a greater extent of injury as well as psychological stress.

The early detection and treatment of lameness is necessary not only on welfare grounds, but also to improve recovery times, and to minimize the extent of injury and inflammation.

Lameness is often (but not exclusively) assessed using a number of discrete scoring systems, all starting at zero, and ranging to five (American Association of Equine Practitioners (AAEP) – globally the most commonly used system), eight (Ross *et al.*, 2003) or ten (predominant in United Kingdom (UK)). An outline of the AAEP and UK systems is provided in **Table 1**. Observer experience (McCracken *et al.*, 2012), observer bias (Arkell *et al.,* 2006), subtlety of lameness (Keegan *et al.*, 2009), limb location (Keegan *et al.*, 2013) as well as scoring system (Viñuela-Ferdnández, *et al.*, 2011) have been shown to contribute to increased variability of such subjective scoring systems. These are discussed further in section **1.3.**

Obel Scale (AAEP)	UK Scale	Manifestation
0	0	Sound
	1	
1	2	Slight lameness in trot (slight head nod in front limb lameness, slight hip hike in hind) on impact and/or during stance phase of affected limb, not detectable in walk.
	3	
2	4	Lameness apparent in trot with more pronounced head nod or hip hike more apparent. Barely detectable at walk.
	5	
3	6	Lameness detectable at walk and trot. Hip hike and head nod evident.
	7	
4	8	Obviously lame at walk, reluctant to place affected limb on the ground. Unwilling to trot.
	9	
5	10	Non-weight bearing lameness.

Table 1: Lameness scoring according to the Obel (AAEP) and UK systems.

1.3 Limitations of gait assessment by human eye

The limitations of gait analysis by human eye have been reasonably well documented. Initially the limitations of human processing must be considered. A preference for symmetry is demonstrated by the classification of asymmetrical objects as being symmetrical more often than symmetrical objects as asymmetrical (Rentschler *et al.*, 1999). Furthermore, in one experiment (Parkes *et al.*, 2009) 20 computer simulations of cubes moving on a computer screen represented the movement pattern of *tuber coxae*; some based on recordings of authentic lame whilst others were entirely artificial. Twelve experienced veterinary surgeons and 24 undergraduate veterinary students were shown the simulations and asked to score the lameness of the ‘horse’ based on symmetry of movement. In both artificial and authentic simulations the accuracy of lameness score increased with increasing asymmetry; an asymmetry of 25% or less was undetectable by both the experienced and non-experienced groups.

However, in the authentic simulation experienced clinicians were consistently more accurate in lameness scoring than in the artificial situation. They were also more accurate than their non-experienced counterparts, purportedly demonstrating their learned sensitivity to relevant movement, rather than asymmetry in general.

The importance of experience in gait assessment is supported by a study which compared three different scoring systems (modified-Obel 0-4; clinical grading system 0-4; and the visual analogue scale 10cm continuum line) as used by 12 undergraduate veterinary students, and 12 experienced clinicians in the classification of 12 lame and 2 sound horses in the viewing of videos of horses on two separate occasions (Viñuela-Fernández *et al.*, 2011). Intra-observer reliability was higher than inter-observer reliability, particularly amongst the students.

Similarly, Arkell *et al.* (2006) found evidence of bias when 18 clinicians (experts and final year students) observed two videotapes of each of seven uni-laterally lame horses (one tape nerve blocked, one unblocked) and an eighth horse unblocked in both tapes, depending on whether they knew or were blinded to nerve blocking. They found clinicians scored a horse's lameness as significantly more severe when they knew of a nerve block. They also found a significantly greater inter and intra-assessor variability amongst students than experts.

Another study (Fuller *et al.*, 2006) investigated this phenomenon amongst experienced vets. One vet witnessed the gait of 8 horses over a course of treatment, and 33 videos were created from these. Lameness scores were derived by this clinician under both live and video circumstances and an intra-assessor reliability of $\kappa = 0.61$ was reported (which in itself is not encouragingly high). However, when shown to three independent clinicians, the inter-assessor reliability was reported as κ = 0.41, only just within the acceptable range.

In order to compare videotaped and live horse assessments and to address the relatively small numbers of subjects in other studies, Keegan *et al.* (2009) undertook a larger study comprising 131 horses each assessed by 2-5 veterinary clinicians (from a total of 16), with a weighted mean of 18.7 years experience. Each animal was assessed first trotting in a straight line (as many times as requested), and then after a full lameness examination (including lunging and flexion tests as requested). Two scores were generated, one a simple 'lame or sound' for each limb after trotting in a straight line, and the second after the full lameness exam using the AAEP scale (0.5 increments were allowed) for each limb. Having trotted in a straight line the vets agreed on lame or sound limbs in 76.6% (κ = 0.44) of trials. This *reduced* to 72.9% (κ = 0.45) after a full lameness examination (according to AAEP scores of >0 or =0). Agreement as to whether a limb was lame or sound was significantly higher in those with an AAEP score of >1.5 (93.1%) than ≤1.5 (61.9%). Accuracy also depended on whether an affected limb was a fore or a hind: agreement on the score of a hindlimb and forelimb with an AAEP score >1.5 was reported as κ = 0.84 and 0.88 respectively, whilst ≤1.5 was reported as κ 0.14 or 0.32 respectively. Whilst levels of agreement κ = 0.44 are marginally better than those reported in video based studies (κ = 0.41 Fuller *et al.,* 2006), both are still disturbingly low given the prevalence of lameness and the reliance on lameness examinations.

Weishaupt *et al.* (2001) compared gait assessments of 22 owner-reported-sound horses by means of a clinical lameness examination (average of three experienced clinicians), accelerometry readings (based on 2 bi-axial accelerometers located at *sternum* and *os sacrum* measuring at 50Hz) and embedded forceplates (measuring at 433Hz). Clinical examinations took place on a concrete runway (including circles, flexion tests and palpation). Force and accelerometry measurements took place on a treadmill operating at 3.5m/s for 20s. Clinical examination found a grade 1-3 lameness (from the 0-5 scale) in all 22 horses. These gradings were defined as 1: 0-2% asymmetry, 2: 2-4% asymmetry and 3: >4% asymmetry for the force and accelerometry readings. A significant correlation was found in the grouping of lameness (as sound, forelimb lame, hind limb lame) between clinical and force (r = 0.51) and accelerometry (r = 0.47) ($p<0.05$), but no correlation was found between accelerometry and force. A significant correlation was also found between clinical examination and force measurements in the identification of the lame limb (r = 0.65, $p<0.05$), but no such correlation was found between accelerometry and clinical examinations, nor force and accelerometry. No correlation was found between any of the three methods in lameness grading. The discrepancies between overground and treadmill analysis may have influenced these results, and this will be discussed further in section **1.5**. Also, the subtlety of lameness may have caused inter-assessor disagreement (which is not reported) as other studies have suggested (Keegan *et al.*, 2009).

Keegan *et al*. (2013) also investigated the use of IMUs in comparison to clinician assessments in a study of 106 horses with a lameness grade of 0-

3 (on a 0-5 scale). Single axis accelerometers were located at the poll (vertical acceleration), pastern of the right fore (angular velocity) and the *os sacrum* (vertical acceleration). Data were acquired as the horse trotted in a straight line whilst clinicians simultaneously evaluated. Clinicians could also palpate, perform flexion tests and lunge horses on hard and soft surfaces. Horses were assigned by each method into groups of right limb lameness greater than left limb, left limb greater than right limb, and equally lame; in both fore and hind limbs. Groups were agreed amongst the clinicians in just 58.8% (κ = 0.37) for forelimb lameness and 54.7% (κ = 0.31) of hindlimb lameness. The best Inertia Measurement Unit (IMU) outputs correlated well with clinicians' identification of which forelimb was lame (R^2 = 0.51), but less well in hindlimb lameness (R^2 = 0.39). Agreement between lameness score according to the best components of IMU and the clinicians' scoring was moderate in forelimbs (κ = 0.41) and fair in hindlimbs (κ = 0.26). These barely acceptable κ values between IMU and clinician are perhaps unsurprising considering the weak inter-assessor agreement. The lack of agreement between clinicians continued to generate problems for validating objective methods in natural lameness and soundness, apart from where experiments were performed assessing horses with known, induced lameness.

McCracken *et al*. (2012) assessed the comparative effectiveness of lameness quantification by three experienced clinicians with IMUs placed at the poll, right pastern, and the *os sacrum*, in 15 horses trotted in a straight line for a total of 120m. The horses were assessed in three conditions 1) before inserting a screw into the custom made shoes, 2) with the screw just touching the sole of the foot and 3) in half turn increments creating increasing lameness. A total of 30 hindlimb, and 30 forelimb trials were performed. The IMU identified the lame limb earlier (with fewer half screw turns) than the clinicians in 58.3% of trials (50% forelimb, 66.7% hindlimb), whilst the clinicians identified the lame limb earlier than the IMU in only 8.3% of trials (3.3% forelimb, 13.3% hindlimb). In 33.3% of cases (46.7% forelimb, 20% hindlimb) lameness was identified by both methods at the same time.

In another experiment comparing IMU measurements with clinician lameness evaluation, Thomsen *et al.* (2010) equipped five horses with a tri-axial accelerometer (at the lowest point of the back) and trotted them up a 25m runway whilst videoing from laterocaudal and laterocranial angles. Horses were then injected with 35ml of saline into the *metocarpophalangeal* joint (or either left or right limb) and trotted up again at 3, 15, 30, 45 and 60 minutes post injection (also filmed). The videos were cut, mixed and watched by two blinded clinicians who were asked to judge lameness on a 0-5 scale. Two symmetry scores were based on eight regular trotting strides from each of the thirty measurements: S based on lateral accelerations (where symmetry scores < asymmetry scores), and A based on vertical accelerations during the stance of each diagonal (where right side lameness < 0 < Left side lameness). Inter-assessor agreement was 70%, while one and two point discrepancies occurred at 23.3% and 6.7% respectively. In 10% of cases the clinicians disagreed on which limb was lame. There was a significant correlation between the mean visual scores of the observer and the S score ($R^2 = 0.63$, $p < 0.0001$), and the A score ($R^2 = 0.606$, < 0.0001).

Overall it seems the reliability of lameness scoring is particularly influenced by the degree of lameness, whether the forelimb or hindlimb is affected (with forelimb being more reliably assessed) and the experience of the observer. It should also be considered that experienced vets who undertake to be part of gait research have particular interest or experience in this specific area, and many vets who have held a license for a comparable number of years are not necessarily as experienced in this field. Similarly, these vets may not be on the rounds for average horse owners as they may be retained by specialist yards or veterinary practices. Therefore the development of an objective tool that does not rely on individual experience would be invaluable for all horse owners and managers.

1.4 Objective gait analysis techniques:

Objective gait analysis techniques fall into two categories: kinematic analysis that quantifies the geometry of gait, historically observed in subjective visual assessment; and kinetic analysis that studies the mass distribution and forces influencing and influenced by movement.

1.4.1 Kinematic

1.4.1.a Optical Motion Capture System (OMCS)

High-speed video has evolved from Muybridge's 12 Hz of 1872 to modern cameras capable of filming at up to 2000Hz. The most popular versions of motion capture system employ either a videographic systems (most usually with markers either on the subject, or added to the film after capture) and optoelectronic (based on the emission and detection of infrared light). The processing (either manual or preprogrammed) of these films allows output of temporal, linear and angular measurements describing the movement of subject through the measuring volume.

Analyses may be two or three-dimensional (2D or 3D respectively); each required anatomical landmark (or marker) must be visible by at least two cameras for 3D analysis to be achieved. Markers may be placed at anatomical landmarks in order to aid (manual or automatic) analysis after filming; the size of these markers should be inversely proportioned to the resolution of the cameras. Spherical or hemispherical markers may aid 3D analysis as the curvature can be seen from different camera angles and so help identify the central point of the marker. The contribution of soft tissue artifacts to skin based markers has been investigated at the *tuber sacrale* and *os sacrum* (Goff *et al.,* 2010) in which skin and bone fixed markers were compared, in terms of *sacral* and *ilio* flexion-extension, lateral bending and axial rotation. There was significantly more movement recorded by skin markers than bone fixed markers in all three planes, in both walk and trot. No correlation was found between the two marker sets, and consequently no algorithm could be produced to extrapolate bone movements from skin markers. It is likely that soft tissue artifacts are to be more significant at trunk and proximal anatomic locations, as well as over joints. Bone fixed markers are of course far more invasive and may be unnecessary apart from in joint motion kinematic studies.

The limitations of OMCS analysis are multifold. First, overground testing requires a large measuring volume to be calibrated and filmed by a large number of (expensive) cameras, depending on the number of anatomical segments required. If markers are placed on hooves, the surface on which the horse is measured may conceal or move markers. Similarly, tack or rider can also affect marker visibility and precision. Lighting conditions around any OMCS measuring volume must be carefully controlled, along with the aperture of each camera. Whether overground or on a treadmill, the movement of the horse or handler may conceal markers, or reflect light that even sophisticated automated systems may confuse as markers, and therefore manual checking of all marker trajectories is mandatory.

1.4.2 Kinetic

1.4.2.a Force plates/shoes

A force plate embedded either into the ground or a treadmill allows quantification of the forces transmitted through individual limbs during stance. These can be categorized as vertical, longitudinal and transverse (of which vertical is of the greatest magnitude) and vary with speed. Accurate foot placement on the plate is required and if two feet strike the plate simultaneously it is not possible to separate their effects. This requires repeated trials and a large amount of data for processing. Force plates have been built into instrumented treadmills, which allow data collection of successive strides, although separation of simultaneous footfalls is still impossible, and they are therefore most widely used for walk and gallop gaits only. These pieces of equipment have to withstand much greater forces than human instrumented treadmills (due to greater speeds and subject masses), making them extremely expensive and rare worldwide (none have been located in the UK. Furthermore the field validity of horses exercising on a treadmill (see section **1.5**), or over a runway-embedded forceplate is debatable in terms of extrapolation to athletic disciplines, due to necessary surface and hoof landing constraints.

Instrumented horseshoes have been developed which provide encouraging results for simultaneous data collection from several hooves in successive strides over a variety of surfaces (Rollet *et al.*, 2004). However, the potential for the shoe to become distorted, the necessity for it to be correctly fitted and removed by a farrier, and the potential for abnormal gait as a result of unfamiliar tactile stimulation (Clayton *et al*., 2008; 2010) make this method not only time consuming and expensive, but potentially misleading.

1.4.2.b Pressure plates

Pressure plates have been investigated as an alternative to force plates for total vertical force, given their mobility and relatively cheap cost. Mean agreement indices were found to be excellent (≥0.92) for timing of peak vertical force, symmetry ratios and stance duration, and moderate (≥0.70) for peak vertical force amplitude and vertical impulse compared to a force plate (Oosterlinck *et al*., 2010). The pressure plate also has the added advantages of visible pressure distribution, and the possibility of separation of separate limb signals when striking simultaneously. However it cannot identify or separate transverse or longitudinal forces and still requires hooves to impact a relatively small area (more difficult with increasing speed), and although inexpensive compared to a force plate, still requires significant initial outlay.

1.4.2.c Strain Gauges

Strain gauges change electrical resistance in response to deformation of hard or soft tissue in contact with the gauge. Each gauge can only measure unilaterally, and thus three gauges are required for 3D measurements. These require invasive and expensive surgical attachment, apart from to the hoof wall to which they can be glued. Whilst this technique has proved useful for research into physiological aspects of anatomy, including hoof wall deformation under a variety of shoeing and surface conditions (Keegan *et al*., 2007) it remains an expensive and impractical tool for industrial gait analysis.

1.4.2.d Accelerometers

1.4.2.d.i Trunk mounted Accelerometers

Accelerometers measure the acceleration and deceleration of the surface to which they are attached. Although they measure kinetics, data can be integrated to velocity, and thereby position, for validation against kinematic measurement. Early accelerometers were uni-axial, although bi-axial and now tri-axial models are available. Modern Inertia Measurement Units (IMUs) can include tri-axial accelerometers, magnetometers and gyroscopes, alleviating the orientation restraints of older technology.

Initial investigations into feasibility of accelerometer use in equine gait analysis were undertaken by Barrey *et al*. (1994) investigating the potential of the *sternum* as a site for accelerometer attachment. One horse was equipped with two uni-axial accelerometers measuring along longitudinal and vertical planes at 50 Hz for 22 seconds across a range of walk and trot speeds (1.6 – 8.9m/s) on a horizontal treadmill. The same horse was also led in walk and trot on a straight asphalt runway with varying degrees of lameness induced by a custom made screw shoe which allowed pressure to be applied to the sole of the hoof. These preliminary results were not compared to any kinematic measurement, but were investigated in terms of reliability. It was found that both vertical ($r = 0.87$, $p < 0.05$) and longitudinal accelerations increased with increasing speed (precise value not given, $p < 0.05$). Vertical acceleration was found to be affected every other step by increasing lameness, and decreasing symmetry between the steps was also noted. However, these results, based on only one horse and not validated against any other system, offered only a preliminary investigation into the use of accelerometers in equine gait analysis.

Simple validation was undertaken by Barrey *et al*. (1995) in which 24 harness trotters with two uniaxial accelerometers (measuring longitudinal and vertical axes) attached to the *sternum* were trotted on a race track for 30s samples at 1) 6.7m/s, 2) 10 m/s and 3) the individuals' maximal speed (average 12.67m/s). These were compared with a video camera filming from a car driving alongside the track. Speed correlated well with stride variables frequency ($r = 0.90$), length ($r = 0.96$) and longitudinal acceleration ($r = 0.87$), for all of which $p < 0.01$.

Leleu *et al*. (2002) attempted to validate the *sternum* for 3 accelerometers measuring at 100Hz (longitudinal, transverse and vertical) against a single camera measuring at 200Hz (2D optoelectronic OMCS system), as horses trotted past on a racetrack. Horses were trotted at speeds of 8.33, 10, 11.66 m/s and maximal speed in a straight line on a sand track. A distance of 40m between the track and the camera allowed 6-10 consecutive strides to be filmed. The three horses wore markers at the hoof, fetlock, knee and hock. The stance period was defined as beginning at the last image before distal extension of the fetlock, whilst midstance was defined as the one in which the knee or hock were vertical, and end of stance was defined as the last image in which the toe was in contact with the ground. Beginning of stance according to this method was found to coincide with the trough immediately before the main peak in the vertical acceleration curve, midstance as the peak itself, and end of stance as the trough after the main peak. No significant difference was found between the techniques according to these methods ($p > 0.05$). Speed correlated strongly with stride length ($r^2 = 0.99$) and stride duration ($r^2 = 0.97$). No significant inter-horse variation was found although this is perhaps unsurprising given the sample size. This method raises a number of concerns. First, the methods for defining beginning and end of stance are questionable; extension of the fetlock may theoretically appear before ground contact, particularly at maximal speeds (a term known as 'flicking the toes'), alternatively beginning of stance may occur earlier and the initial energy absorption taking the form of hoof slip (see section **1.4.2.d.ii**). Second, the end of stance may be unclear where the horse is trotting on sand and the toe is concealed. Third, the issue of midstance occurring as vertical alignment of the knee or hock requires the static conformation of the horse to be consistent with this, but no such information was provided. Fourth, the use of a single camera may have necessitated this definition of stance by the lack of 3D data, and its distance from the track may have limited the clarity and thereby the accuracy of the techniques. Finally, although the potential influence of advanced hind limb placement was briefly mentioned in the discussion, no description was offered as to whether it was apparent and if so whether stance was defined by the front or hind legs.

Pfau *et al*. (2005) undertook a thorough investigation into a method for deriving displacement data from a tri-axial IMU (accelerometers and gyroscopes) (250Hz) in walk, trot and canter on a treadmill. These were attached by a custom made harness to the withers of a Thoroughbred horse, beneath spherical OMCS reflective markers on stalks indicating longitudinal, vertical and transverse axes. Two cameras comprising an optoelectronic system measuring at 240Hz filmed the horse. Another IMU was attached to the dorsal midline of the left fore hoof, the transmitter and battery for which were wired to an elastic bandage of the cannon bone. A total of 35 strides were analysed in all axes and showed a relative error of ±3.3% for walk, ±6.5% for trot and 6.7% for canter. The low relative error of IMU data in comparison to a 3D OMCS system offers encouraging results for this line of investigation. The authors advocate the use of the limb mounted accelerometer for research purposes, as validated by Witte *et al.* (2004) due to the improved accuracy that must be gained by its proximal location to the impact. Therefore no method is given for identifying beginning and end of stance from a trunk IMU alone. However, although boots encompassing the cannon are common for equine exercise and despite the relatively low weight 310g (<1% limb mass) of the equipment in this location, research has shown the effect of tactile stimulation of the limbs to result in gait alterations (Clayton *et al*., 2008, 2010) that may suggest this technique is inappropriate in sensitive horses. Further, industrial use (as opposed to research) may favour practicality over precision as long as reliability is not compromised. The use of the withers as a site requires the use of the custom made harness (with which the horse must be familiarized), and is also at some distance from the centre of mass (CoM) according to Buchner *et al*. (1997), which theoretically may limit its accuracy in terms of energetics measurement without correction. The site may also contribute artefacts from soft tissue, or indeed the harness itself that may negatively contribute to accuracy.

Further studies have investigated the use of other trunk locations as accelerometry sites. Starke *et al*. (2012) investigated the *os sacrum* as a site from which hindlimb activity could be identified. Ten sound horses were equipped with IMUs (triaxial accelerometer and gyroscope measuring at 100Hz) at that location, as well as Global Positioning System (GPS) receivers (4Hz) at the first lumbar vertebra and the poll, as well as a biaxial accelerometer (1000Hz) on the dorsal midline of the left or right hind hoof, wired to a logger in a modified boot on the cannon. Horses were walked and trotted on a tarmac surface, in a straight line as well as on a circle (diameter 10-14m) at the individual horse's preferred, slow and fast speeds. Minimum vertical velocity indicated beginning of stance in walk (mean difference from hoof data 15ms (18)), whilst in trot zero crossing was found to coincide with the beginning of stance according to hoof data $a\underline{Z}$ (Witte *et al*., 2004) (mean difference -4(14) to 12(7) ms). The use of pelvic roll to identify limb in stance was also assessed in these sound and 8 lame horses, and was found to be 100% in all conditions. This study offers a useful stride segmentation technique for hind limbs that allows inter-stride comparisons for regularity and intra-stride symmetry. Unfortunately no method for identifying the end of stance was presented. Attachment to the *os sacrum* is likely to require skin glue and clipping of the area so some owners maybe unwilling to allow this prior to competition. The use of the *os sacrum* to identify hind limb lameness however may be particularly useful given its ambiguity to subjective identification (see section **1.3.2**), as well as an industrial requirement for symmetrical power behind most specifically in dressage. However, this site has been shown to be subject 'unacceptable levels' (Goff *et al*., 2010) of soft tissue artefacts when compared to bone fixed markers at the same site. This will limit precision, although the evidently high degree of accuracy presented here still proves its value for reliable stride segmentation.

One study (Olsen *et al.*, 2012) undertook an in depth assessment of trunk mounted IMUs. Up to six experts assessed seven horses of various breeds, of which three were found to be mildly lame, and three had mild to moderate ataxia. The horses were equipped with an 18g IMU on each limb at the cannon bone attached by custom-made boots. Five 10g IMUs (200Hz) were also attached at the withers, the fourth lumbar vertebrae, the *os sacrum* and over each *tuber coxa*, by means of double sided adhesive tape. The horse was stood still at the beginning and end of each test in order to aid sensor orientation, and the test itself comprised of the animal being lead at its preferred walking speed down a 25m runway with an embedded force plate (500Hz), and a synchronized 12 camera optoelectronic OMCS, with reflective markers over all IMUs and the hooves (amongst others).

Beginning and end of stance was defined in the forceplate data at a threshold of 10N of vertical force. A total of 123 front limb and 119 hindlimb stance phases were included by all measurement techniques. A range of outputs was compared including vertical and horizontal velocities and accelerations of the limb mounted IMUs. Vertical acceleration and horizontal displacement of limb mounted IMUs were recommended for beginning and end of stance of the hind limbs respectively (ICC: 0.9021, LLoA = -54.13, ULoA = 54.52), in comparison to the forceplate. Horizontal velocity and acceleration of limb mounted IMUs were found to be most accurate for beginning and end of stance of the forelimbs respectively (ICC = 0.8391, LLoA = -73.80, ULoA = 73.75), in comparison to the forceplate. Vertical velocity of the *os sacrum* was found to provide hind limb beginning of stance timings with good accuracy (3ms, LoA -11 to 17ms). However end of stance was not identifiable, nor were beginning or end of stance from other trunk mounted IMUs. The supplementary information for this article *did* suggest that longitudinal velocity of the withers could identify beginning and end of stance of the forelimbs, whilst longitudinal acceleration of the *os sacrum* could identify the same for the hindlimbs, although numerical data was not provided. It is unfortunate that the ICCs are not presented for other trunk locations, although the *os sacrum* results show that trunk measurements are accurate at least for beginning of stance of the hind limbs. Although the withers, 4th lumbar and *tuber coxae* results were presumably less accurate for the front limbs, another trunk technique (such as the *sternum*) may yet yield promising results.

1.4.2.d.ii Limb mounted IMUs

The accuracy of limb mounted IMUs has been validated and utilized in a range of studies. Witte *et al*. (2004) proved the potential of predicting vertical Ground Reaction Force (GRFz) from duty factor, in a study comparing foot mounted uniaxial accelerometers on six Warmbloods (walk and trot) and four Thoroughbreds (canter) over an 80m dirt and concrete runway with an embedded forceplate, all data being collected at 1000Hz. A forceplate threshold of 50N was used to define stance, and a blinded clinician assessed accelerometer data before being deducting IMU derived data from forceplate data to provide an error between the techniques. Beginning of stance absolute error means were reported as 2.4ms for walk, 1.8ms for trot, 2.0ms for non-lead canter limb, and 3.0ms for lead canter limb. End of stance absolute error means were reported as 3.6ms for walk, 2.4ms for trot, 5.0ms for non-lead canter limb, and 2.8ms for lead canter limb. The mean value of the amplitude error compared to GRFz was 0.3N kg^{-1} at walk, 0.8N kg^{-1} at trot, 0.6N kg^{-1} for non-lead canter limb and 0.4N kg^{-1} for lead canter limb. The orientation of the sensor being along hoof wall (as opposed to perpendicular to the ground) reduces the rotation components prior to foot off and improves accuracy over other studies that have struggled with this component. Witte *et al*. (2004) recommended the use of a correction factor between lead and non-lead canter limbs for GRFz calculated from duty factor.

The use of the hoof as a site of accelerometry in order to assess the shock and impact forces has also been investigated. Hoof slip is an important feature of beginning of stance that can affect both performance and orthopedic health. It was investigated in part by Holden-Douilly *et al*. (2013) in four harness trotters moving at 7m/s on wet sand, by means of a videographic system, a force shoe and a triaxial IMU. Mean hoof slip distance across 62 observations was 4.39cm (1.51) according to IMU data, but 3.61cm (1.49) according to kinematic data. Hoof slip is composed of heel only and hoof-flat slip, the rotation of which can lead to inaccuracies in both kinematic and uni or bi-axial accelerometer data. In this study, first appearance of high-frequency vibrations in the IMU data coincided with heel strike according to the force shoe, and the maximal peak in vertical deceleration coincided with hoof flat. The forwards rotation (pitch) of the hoof on wet sand led to an overestimation of slip distance of up to 47.3% where pitch ≥10° according to kinematic data, but only 4.9% in IMU data. Although this degree of rotation was present in only 3.3% of trials, whilst 73.3% of trials had ≤5° pitch. This data is significant because it emphasizes the necessity of a clearer definition of stance: different studies have defined beginning of stance using a force threshold (Olsen *et al*., 2012; Witte *et al*., 2004) using an embedded force plate and a hard surface which have been found to hold different slipping properties than sand or dirt (Holden Douilly *et al*., 2013). The use of longitudinal velocity, acceleration or position (Buchner *et al.*, 1993) will most likely exclude slipping distance. Whilst these will not cause problems for stride segmentation techniques, it cannot be possible to accurately separate stance from swing, unless hoof slip is considered and stance defined as either including or excluding the phenomenon.

The forces to which horse's limbs are subjected have been investigated (Gustås *et al.*, 2001; 2004) as well as the effect of surface (Chateau *et al*., 2009; 2010; Ratzlaff *et al*., 2005; Setterbo *et al*., 2009; Gustås *et al.*, 2006) shoeing properties (Schaer *et al*., 2006) and the influence of boots and wraps (Luhmann *et al.*, 2000). It has been found that drier sand surfaces reduce shock and impact forces during landing, but are also associated with a shorter stride length and frequency, both of which are correlated to maximal speeds. It should also be remembered that force through the limbs stimulates skeletal adaptations to training including increased bone density that may not occur over softer ground. Further, deeper going is more typically associated with ligament injuries, for example in dressage horses (Murray *et al*., 2010).

The use of accelerometers has provided practical insights into the energy requirements of working horses due to their practical overground advantages over laboratory experiments. Parsons *et al*. (2008) investigated the mechanical energy and trunk movements affected by incline, using an IMU (tri-axial, 250Hz) at the withers and four hoof mounted accelerometers on six national hunt racehorses as they undertook their normal gallop exercise (9-12m/s) up a woodchip track of 1077m. The data were categorized as 0-2% incline (N = 198, mean speed = 10.4m/s, mean slope = 1.2%) and 10-15% incline (N = 156, mean speed = 10.2m/s, mean slope = 12.8%). Dorsoventral displacement was significantly greater during level galloping than inclined galloping ($p = 0.047$) and was significantly different between horses ($p=0.001$), but no significant differences were found between the two conditions in terms of craniocaudal or mediolateral movement, or maximal velocity ($p > 0.05$). Pitch difference between horses was insignificant ($p > 0.05$) but was affected by incline ($p = 0.018$). The results showed that changes in trunk motion effected by incline could not fully explain the increased mechanical work done by the trunk during inclined galloping, which are instead explained by the significant increase in linear mechanical work ($p < 0.001$) and the mechanical cost of transport ($p < 0.001$).

Pfau *et al*. (2006) used the same sites (withers and hooves) for mounting IMUs (tri-axial, 250Hz) to investigate mechanical energy fluctuation during gallop of seven Thoroughbreds at a steady speed for 600m and then increasing to a maximal speed for 400m, consistent with their daily exercise. A total of 613 strides were automatically segmented from the data. Minimums in external work were extrapolated as 250mm below and 200mm behind the sensor. Craniocaudal and dorsoventral displacement was sinusoidal and of limited variability between strides and horses. Mediolateral displacement and velocity were more variable within and between horses, but showed distinct differences in left versus right lead canter. Whilst craniocaudal and mediolateral displacements increased with speed, (craniocaudal 75mm at 7m/s to 89mm at 17m/s) dorsoventral displacement decreased (185mm at 7m/s to 83mm at 17m/s).

The advancing technology of IMUs makes overground, high-speed analysis possible. However the algorithms produced to extrapolate from skin-mounted markers to a CoM rely on the location of CoM as described by Buchner *et al*. (1997) based on the segmented analysis of six Warmblood cadavers. It is widely acknowledged that this can only be accurate if

Warmblood conformation and weight distribution is similar to the horses being studied; given the extensive breeding programs designed to change the shape and muscle distribution of breeds for specific disciplines this should perhaps be treated with caution. Similarly, whilst the 'dead weight' of a segmented horse will have a static CoM, a moving animal is likely to have a moving CoM. This was verified in one study by Nauwelaerts *et* al. (2009) that compared a rigid body model with a deformable body model in six sound horses (a variety of breeds and shapes) using a trunk mesh of 45 passive markers as the animals stood square (from which CoM was projected for the rigid model) and walking and trotting in hand at a range of speeds (0.7 – 4.3m/s) (from which CoM was measured for the deformable model). The two methods produced significantly different results in total mechanical energy profiles (including maximum and minimum peaks) and these differences increased with Froude number. The differences were small in the vertical plane, but large in the transverse and longitudinal planes and were significant enough for the calculated energy expenditure to differ by 25% between the two models. Further, one horse that was significantly heavier than the others demonstrated a significantly different energy profile from the others according to the deformable model. This study goes to support the logical concerns over predicting CoM movement based on a restricted study of only six Warmblood cadavers (Buchner *et al*., 1997).

In addition to lameness, impact and energy, accelerometers have been used to describe and analyse stride parameters in horses from a range of disciplines and abilities. Barrey *et al*. (2001) attached two uniaxial accelerometers (50Hz) to the *sternum*, measuring in the longitudinal and vertical planes to assess the stride characteristics of 30 racehorses specializing in a range of distances to a variety of abilities. Horses were galloped at maximal speed (mean 15.26m/s, SD = 2.07) along 800m of dirt track. The velocity was correlated with stride length (r = 0.81) and stride frequency (r = 0.56). However, performance (average earnings per start) was negatively correlated with stride length (0.32), and positively with stride frequency (r = 0.42), diagonal dissociation between lead hind and non-lead fore (r = 0.43) and ground contact duration (r = 0.41). Horses that won short distance races (<1400m) had a longer relative ground contact duration (p<0.05). However, it may be misleading to describe stride parameters in terms of velocity or stride length compared to others within a cohort, and financial race winnings over horses not included in the cohort. It must also be understood that there are inevitably differences in maximal speed (and presumably the connected stride parameters) under training conditions as opposed to in race conditions. Further, given the distance from the limbs, with no hoof-mounted accelerometers for comparison combined with the 50Hz measurement frequency, the accuracy of detailed stride characteristics (such as diagonal disassociation) may be debatable. Barrey *et al*. (2001) argued that a maximal stride frequency would be 3Hz, and therefore 50Hz was an adequate measurement frequency, particularly given the power spectra used. The precision of the technique certainly seemed to yield practical, useful results on the whole.

The relationship between stride parameters and performance ability has also been investigated in trotting horses. Leleu *et al.* (2005) used the site proposed by Barrey *et al*. (1995) and validated for use in trotters by Leleu *et al*. (2002) to compare elite (Index of Trot (ITR) ≥ 115, n = 52) and medium (ITR < 115, n = 52) performers in terms of stride characteristics as they trotted a 400m straight line at 8.5, 10, 11.7m/s and maximal velocity. The three uni-axial accelerometers measuring in the longitudinal, vertical and transverse directions (100Hz) were also compared with electromagnetic tachymeter (on the wheel of the sulky) and a GPS system (on the shaft) to contribute velocity feedback to the driver as well as data. Stride length and frequency, as well as longitudinal, vertical and transverse activities (integral of power spectrum from Fast Fourier Transform of acceleration signals) significantly increased with speed ($p< 0.0001$). Symmetry was not significantly affected, whilst regularity between strides, right stance duration and right propulsion duration (midstance to toe off) significantly decreased with speed. Velocity, symmetry, regularity, and the three activities were not significantly different between groups. Elite trotters showed significantly higher stride frequencies, stance durations and propulsion durations. The correlation matrices were found to be significant between ITR and stride frequencies ($r = 0.15$), stance durations ($r = 0.22$) and propulsion durations ($r = 0.22$). The matrix between stride length and ITR was not significant, but was with cumulative earnings ($r = 0.11$), where $p>0.05$ for all comparisons. The lack of significance between stride length and ITR is consistent with the problematic comparison of horses inside a cohort with those outside it against whom they are ranked, which may have contributed to a negative correlation between these characteristics described by Barrey *et al.*, (2001). The temporal stride parameters rely on the methods explained and reviewed on page 16 when used by Leleu *et al*. in 2002. However, concerns over the significance of hoof slip, the definition of stance and swing of the diagonals and conformation influences on the definition of 'midstance' remain applicable to the accuracy (although not the precision) of these results.

Witte *et al*. (2006) used the methods validated (Witte *et al.*, 2004) to investigate the effect of speed on fore and hind duty factor and predicted limb force of galloping racehorses, equipped with hoof mounted accelerometers wired to cannon bandages containing batteries and transmitters. Horses were cantered at a steady speed for 600m and at maximal gallop for 400m. Six horses provided 5642 strides of data, ranging in speed from 9-17m/s, all horses achieving a minimum of 16m/s. With increasing speed the stance duration decreased, and was significantly higher in hind than forelimbs across speeds ($p = 0.003$). Protraction duration also decreased with increasing speed, but was significantly greater in fore than hindlimbs ($p = 0.007$). Stride frequency increased linearly with speed ($r^2 = 0.99$). Duty factor decreased curvilinearly with speed ($r^2 = 0.99$ and 0.98 for hind and forelimbs respectively), and hind was significantly greater than fore ($p = 0.0040$). The stance length (distance travelled by trunk during stance phase of individual limbs) increased with speed, and was significantly higher in hind than forelimbs ($p = 0.002$) across speeds. Aerial:contact phases remained approximately 27:73 throughout the speed range. Although a harness mounted IMU was present, data were not presented. It would be interesting to see published data comparing these with those from the hoof-mounted accelerometers. The stance length presented (as opposed to stride length of other studies) is comparable when considered with the percentage aerial to stance phase (27:73), and is consistent with others' findings.

Whilst it is very difficult for a cohort's stride parameters to be compared in terms of performance when they are not racing one another, the use of such studies is not merely a descriptive correlation but also enables analysis of which intrinsic stride characteristics make a high performer, and which can be affected by training or fitness.

Ferrari *et al*, (2009) therefore attempted to approach the training question in a direct method by assessing the stride characteristics of eight National Hunt horses after the summer break (roughly three months) and after six months training. All horses had previously been trained for one to three seasons. Horses were assessed by means of one accelerometer attached to the left fore hoof wall (with a battery and MP3 recorder in the brushing boot , and equal 112g weighting in the opposing boot) as the horses galloped in pairs (at self selected speeds but staying head to head) up a 800m all-weather track with an overall elevation of 50m. This gallop was performed three times by each horse both pre and post training. The maximum speed reached up the gallops did not significantly increase between the conditions ($p > 0.05$). Nor did the mean stance time change significantly ($p = 0.4$) which is in contrast to other pre/post training studies of racehorses (Rogers *et al.*, 2004), although this may not be comparable as it examined the trot, not the trained gait (gallop), and studied two-year-olds in their first season. Ferrari *et al*. (2009) described a significant decrease in the protraction time of the measured limb before and after training ($p < 0.001$).

There was an accordingly significant increase in stride frequency after training ($p < 0.015$). Whilst this is in agreement with other studies, the fact there was no difference pre and post-training in overall speed, or in stance time, suggests instead that training produced a longer airborne phase. At constant speeds the contact:aerial phases of the stride is thus a smaller ratio than during acceleration. This is in contrast to Witte *et al*. (2006) who found a constant ratio of approximately 73:27 across speed 'bins' forming a continuum of acceleration up to and including maximal speed. However it is consistent with the range presented by Barrey *et al*. (2001) of ground contact (as percentage of stride duration) 39.8 – 78.6%. These suggest in part that training is likely to make the ground contact time more efficient at propulsion.

Many all-weather training tracks (and racetracks) include inclines, and the effect of these on stride parameters has been partly investigated by Parsons *et al*. (2008), in six Thoroughbreds galloping along an all weather track with accelerometers on each hoof. Incline was categorized as level (0-2%) and incline (8-12%), at a range of speeds categorized into 4, including 9.5m/s and 12.5 m/s (9 - 150 strides per speed on the level, 4 - 72 strides on incline). Duty factor increased between speed conditions, and between level and incline galloping, although the effect of incline was not significant in forelimbs, it was significantly greater in hindlimbs ($p = 0.01$). The stance duration was consistently greater in hindlimbs than forelimbs in both speed categories, the difference being significant during incline galloping (p =

0.01). The protraction duration decreased across the speed ranges, in both fore and hind limbs between level and incline galloping ($p < 0.001$), with hindlimbs showing shorter durations across the speed range, although this was only significant during incline galloping ($p = 0.03$). Stride frequency significantly increased across speeds between level and incline galloping ($p < 0.001$). This is concordant with the decreased protraction duration "*due to interference with either the 'catapult mechanism' of tendons in the distal limb, or the limb arc causing an earlier contact time*" (Parsons *et al.*, 2008). These are significant findings, particularly when it is considered that many stride parameter studies take an average across a gallop and describe the overall elevation without segmenting it within the whole datum, thereby potentially skewing results.

1.5 Treadmill versus overground locomotion

Treadmill testing has advantages and disadvantages in comparison with overground testing. The environmental influences such as wind speed and direction amongst other weathers and the track conditions can be standardized with accuracy impossible in outdoor locomotion. Invasive techniques such as endoscopy and oxygen comparison were historically impossible overground, although modern technological advances have since made this possible. Similarly, OMCS and forceplate systems are relatively limited in the number of overground measureable consecutive strides due to the limited measuring volume, which is partially resolved by treadmill testing. Furthermore, any wired system is confined to treadmill usage unless the equipment is attached either to the harnessing or sulky. Inter-stride comparisons can be made due to the artificial control of velocity, although one significant study discovered that belt speed decreased during the stance phase by 9% (Buchner *et al.*, 1993). This does not preclude the accuracy of inter-stride comparisons.

The field validity of treadmill testing and exercise has been investigated by a small number of conflicting but nonetheless important studies. Barrey *et al*. (1993) investigated 7 horses overground and on a treadmill using a video camera at speeds ranging from 1.6 – 10 m/s, and at 0% and 3.5% incline. It was found that stride frequency was significantly higher overground than on the treadmill, whilst stride length was significantly lower overground than on a treadmill ($p < 0.01$). The incline was not found to have any significant effect.

Conversely, Gomez Alvarez *et al*. (2009) found no difference in stride length duration or stance duration in 6 horses trotting overground on a gravel track and at matched velocities on a treadmill. Gomez Alvarez *et al* (2009) did however find a significant ($p < 0.05$) decrease of lateral flexion/extension, and also a greater degree of symmetry on a treadmill than overground. This might be explained partly by the enforced velocity creating inter-step symmetry (as well as intra-stride regularity), and also by the treadmill surrounding barriers enforcing a straightness of the horse along the direction of movement.

Buchner *et al*. (1993) investigated differences in locomotion on rubber, tarmac and on a treadmill in 10 horses, and found a greater stance duration of the forelimbs on a treadmill than overground, which contributed to the disappearance of the advanced hind limb placement apparent in overground observations and instead exhibiting advanced forelimb placement on a treadmill. The vertical displacement of the withers also significantly reduced on a treadmill compared to rubber overground.

In experiments by Barrey *et al*. (1993) and Buchner *et al*. (1993) horses were ridden overground and unridden on the treadmill. This may have led to discrepancies, as suggested by Sloet *et al*. (1997) who investigated the stride parameters and work done by horses on a level treadmill on at a 6% incline in unloaded, mounted, and lead-loaded conditions. An increased stance duration was found during level trotting in mounted and lead-loaded conditions compared to unloaded conditions. The maximum fetlock extension and protraction angle of the forelimbs was significantly greater in mounted and lead-loaded conditions than unloaded. Further, the increase in stance duration of the hind limb, decrease in maximum fetlock extension and increased retraction angles fore and hind, and the increased tarsal joint angles at impact and their range of motion were all significantly different in inclined compared to level conditions, in accordance with Parsons *et al*. (2008).

Treadmill exercise is frequently used for rehabilitative purposes due to the greater degree of control of a horses speed and straightness, encouraging symmetrical movement without the need for a rider. Treadmill testing also offers a reliable standardized platform from which validity studies can be undertaken, although the results themselves cannot be assumed to be indicative of overground conditions.

1.6 Justification of the current study

The variability of subjective gait analysis due to observer experience, observer bias, scoring system, and particularly in mild and/or hindlimb lameness has led to the development of objective gait analysis tools. Many of these require expensive and complicated equipment and software, purpose built testing areas (such as embedded forceplates), or user training.

Gait examinations are frequently undertaken as part of research, but also as veterinary assessment, training monitoring, pre-purchase examinations and on day-to-day welfare grounds. There is therefore a clear need for an easy to use, reliable and objective gait analysis tool that could be used in sound and lame horses in a variety of settings throughout the practical horse industry.

1.7 Aim

This study aims to investigate the validity of the *sternum* as a site from which to measure stride characteristics of horses trotting on a treadmill, using both OMCS and an IMU system.

1.8 Hypotheses to be tested

H_1: There will be no difference found in beginning and end of stance times between methods employing OMCS hoof trajectories *v*X̲, *v*Z̲ and *p*Z̲.

H_2: There will be no evidence of advanced hindlimb placement according to OMCS hoof trajectories in unridden horses trotting at self-selected speeds on a treadmill.

H_3: Beginning and end of stance according to OMCS hoof trajectories will also be detectable by OMCS at the sternum.

H_4: The diagonal in stance will be detectable by both OMCS and IMU from the sternum.

H_5: There will be no difference between IMU and OMCS measurements from the sternum in terms of amplitude and timing of peaks and troughs.

2 Method

2.1 Experimental design

A concurrent validity procedure was used to establish the effect of the swing and stance phases of horses' limbs on a trunk marker located at the girth, as they exercised on a treadmill.

2.2 Laboratory

The experiments were conducted at Hartpury College Equine Therapy Centre in a well-ventilated barn, with floor comprising rough concrete for non-slip properties, and coarse rubber surrounding the treadmill for non-slip and cushioning properties. There was adequate space for safe passage of handlers and experimenters around the measuring volume and the cameras. A path was left clear to and from the treadmill for the horses.

2.2.1 Treadmill/ Measuring volume

The treadmill used was a certified Sato I (Sato, Uppsala, Sweden), which allows speeds ranging from 0-16m/s and 0-10% (or 6 degree) incline, whilst surrounded by strong bars to ensure the safety of horses and handlers. The treadmill had a wall mounted LCD display device showing speed and slope to the operator. A high power fan was placed in front of the treadmill to cool the horse during exercise.

2.3 OMCS

2.3.1 System Specifications

The OMCS used seven Qualisys ProReflex cameras using non-hazardous infrared strobe lighting to illuminate markers. These were wired to a laptop computer running Qualisys Track Manager (QTM) 1.9.2xx, a Windows-based data acquisition software with an interface that allows 3D motion capture and real-time camera information (Qualisys AB, Gothenburg, Sweden).

2.3.2 Camera set up

The seven ProReflex cameras were set up surrounding the measuring volume, with three each side of the treadmill with a minimum angle of incidence of 30° (for 3D accuracy), at a height of roughly 1.7(m) pointing down at the treadmill (to avoid potential confusion between camera flashes and markers), and the remaining camera square in front of the treadmill at roughly 0.6m to capture between the horses' front legs.

With the volume base described by a marker in each corner, it was ensured that each marker was visible by at least two cameras, and that the camera focus and aperture was appropriate.

See Appendix 1 (Standard Operating Procedure for QTM and equine treadmill testing) for further details.

2.3.3 Calibration

Calibration was done by means of the calibration kit, comprising a 750mm Wand and an L-shaped reference structure to describe the frame coordinates. The frame described the axes of the measurement volume as <u>X</u>

= longitudinal (or craniocaudal aspect of the horse when present), Y = lateral (or mediolateral aspect of the horse when present) and Z = vertical (or dorsoventral aspect of the horse when present) (See **Figure 1**).

Using the QTM calibration dialog, calibration was undertaken (at a 15 second duration) by means of spinning the wand the full X and Y of the measuring volume to a Z height of 0.7m, in all three directions in order to ensure proper scaling of all three axes.

See Appendix 1 (Standard Operating Procedure for QTM and equine treadmill testing) testing for further details.

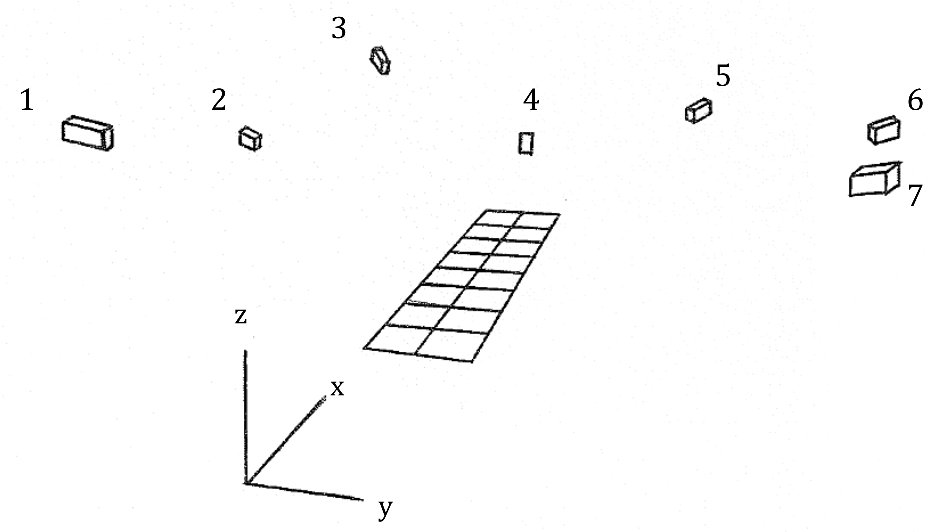


Figure 1: Arrangement of cameras surrounding the measuring volume.

2.3.4 Markers

A circular (2.5cm diameter) self-adhesive marker was attached to the lateral aspect midline of each hoof (see **Figure 2.A**), and one hemispherical marker was attached to the ventral aspect of the girth by means of strong double sided tape; this marker was thus placed over the *sternum*, between the *pectoralis profundi* (see **Figure 2.B**).

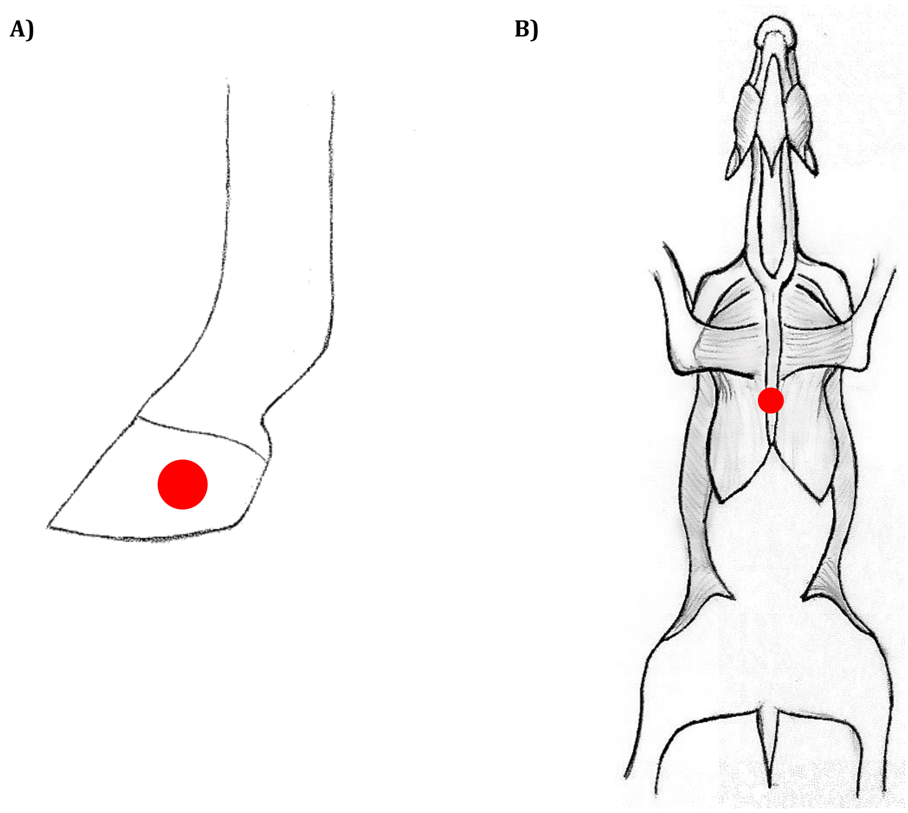


Figure 2: Placement of OMCS markers and Base IMU.

A) Lateral view of a hoof, demonstrating the position of a hoof marker on the lateral aspect midline. B) Ventral view of a horse, demonstrating the position of the Girth Marker and Base IMU, over the *sternum* between the *pectoralis profundi.*

2.4 Inertia Measurement Units

2.4.1 System Specifications

The IMU system used two Pi-Nodes (Pi-Node, Philips, Eindhoven, The Netherlands). Each Pi-Node estimated its spatial orientation using accelerometers, magnetometers and gyroscopes. The calibrated digital conversions of these were sent to the host PC wirelessly via Bluetooth, with the following properties controlling sampling:

- **usPerSubSample** – expressed in microseconds, this defined the sample rate of the Pi-Done, before decimation. For this procedure the value was 10000 (which is equal to 100Hz).
- **subPerSample** – this defined the decimation factor. For this procedure the value was 4 (yielding an effective sample rate of 25Hz when usPerSubSample is 10000).
- **samplePerPacket** – defined how many samples (after decimation) were transmitted in one RF-packet. For this procedure a value of 3 samples per packet (of 25Hz decimated, 100Hz before decimation) was employed.

See Appendix 2 (Standard Operating Procedure for Equine Phillips Pi-Node) for further details.

2.4.2 Base and Extent IMUs

Two IMUs were used for each measurement:

2.4.2.a The Base IMU

The Base IMU was attached to the inside of the surcingle by means of strong double-sided tape over the *sternum* and between the *pectoralis profundi* (see **Figure 2.B.**) this placed it immediately beneath the OMCS girth marker (see section **2.3.4**).

2.4.2.b The Extent IMU

The Extent IMU was placed near to the receiving laptop on a stable surface. No equipment was available to automatically synchronise the OMCS and IMU systems at the measurement stage. Therefore the IMUs' measurements were begun, and on starting and ending the OMCS measurements the Extent IMU was tapped, in order to create an event marker that could be used to aid manual synchronization between both IMUs and the OMCS signal (see section **2.10.3**).

2.5 Ethics

The Hartpury College Research Ethics Committee approved the study.

Veterinary approval, veterinary supervision and Home Office licensing were not required for this non-invasive procedure in which no animal was required to do anything not consistent with typical daily routine.

Informed consent was provided by Hartpury College, who either owned the horses or was responsible for all duty of care as the contracted keeper.

2.6 Inclusion criteria

- Horses must be riding horses.
- Horses must **not** be bred for, trained to, or have competed at an elite level in any discipline.
- Horses must have undergone the treadmill familiarization procedure (see section **2.7**), and be accustomed to treadmill exercise.

- Horses must be as far as possible temperamentally suited to testing, as suggested by the treadmill familiarisation procedure (see section **2.7**).
- Horses must be, to the best of the professional keeper's knowledge, sound and of good health.

2.7 Familiarisation

All horses were familiarised to treadmill exercise (Buchner *et al.,* 1994 *b*) in the weeks prior to testing. In this protocol, familiarization took place in two stages.

Initially, the horse was introduced to the treadmill room, and allowed to become familiar with the sights and smells. When the horse was calm in this situation the treadmill was switched on and off until the horse became comfortable with the noise of the motor and belt. Then the horse was lead on and off the treadmill, and eventually taught to start walking and halt on the treadmill. This was taught over a number of sessions (depending on the individual's reaction to the situation), by means of vocal encouragement, the use of the whip where necessary, and handfuls of grain. Eventually the horse was asked to trot on the treadmill. This comprised the first stage.

The second stage taught the horse to move between gaits (walk, trot and canter) fluidly on command, whilst keeping to the front of the treadmill. When the horse could calmly undertake these transitions, the second stage of familiarization was complete and the horse is ready for testing.

See Appendix 3 (Standard Operating Procedure for Equine Familiarisation Sato I) testing for further details.

2.8 Subjects

Hartpury College staff selected 16 horses from their yard that matched the inclusion criteria (see section **2.6.**)

2.9 Procedure

Each horse, equipped with markers (see section **2.3.4**) and the Base IMU (see section **2.4.2.a**), was led to the treadmill by the handlers. Initially a warm up was undertaken (8 minutes):

Gait	**Speed (m/s)**	**Incline (°)**	**Duration (minutes)**
Walk	1.8 – 1.9	0	4
Trot	3.0 – 4.5	0	2
Canter	9.0 – 9.5 (to encourage the transition) then stablised at 7.0 – 8.0	5	2

Table 2: Treadmill warm up protocol undertaken immediately prior to testing.

The horse was then returned to walk (via trot) for 3 minutes (1.8 – 1.9m/s; 0° incline).

After this rest, the horse was encouraged to trot on again at self-selected speed according to the handlers' knowledge of the individual horse from familiarization procedures (range 3.0 – 4.5m/s) for 3 minutes. Upon settling in trot, 3-5 ten-second samples were taken:

The IMUs were started first, and upon starting the OMCS the Extent IMU was tapped, creating an event marker by which to manually synchronise the two signal types (see section **2.10.3**). It was tapped again at the end of the OMCS sample collection. This process was repeated for each of the 3-5 ten-second samples.

The horse was then brought back to walk (1.8 – 1.9m/s) for at least two minutes to cool down. The horse was then removed from the treadmill and returned to the stable, where the markers and IMU were removed and the horse rugged appropriately to avoid any post-exercise chill.

2.10 Data Handling

2.10.1 OMCS

2.10.1.a Marker identification and labeling

An automatic marker identification and labeling system was created in QTM, but manually checked throughout every sample. Any time the cameras lost sight of any marker (typically caused when handler or treadmill structures obscured markers, or in certain light conditions) there was the potential for the program to fail to re-identify the marker when it next became visible, or for the program to misidentify irrelevant light points (such as reflections from metal equipment) as significant markers.

2.10.1.b Spline Gap Filling

The spline gap filling function in QTM was employed only where individual gaps consisted of no greater than 1% of the total sample time. This was to prevent the simulation of a misleading trajectory from too large a gap.

2.10.1.c Export to Excel

Labelled positional (p) marker trajectories were exported in a raw, unfiltered format as a .tsv file for further handling in Microsoft Excel. The p

values in meters [m] were used to derive velocity (v) and acceleration (a) values according to the equations, were *dt[s]* refers to time sample intervals

$$v\,[\frac{m}{s}] = \frac{\Delta\, p[m]}{0.01dt[s]}$$

$$a\,[\frac{m}{s^2}] = \frac{\Delta\, v\,[\frac{m}{s}]}{0.01dt[s]}$$

2.10.1.d Savitsky-Golay smoother

A Savitsky-Golay (SG) smoother was used in order to preserve the maxima and minima as well as avoid anomaly based skewing. The preferred extent (see **Figure 3.C**) and application timing was selected after in-depth comparisons, ensuring the preservation of significant events, as well as smoothing anomalies and missing data segments.

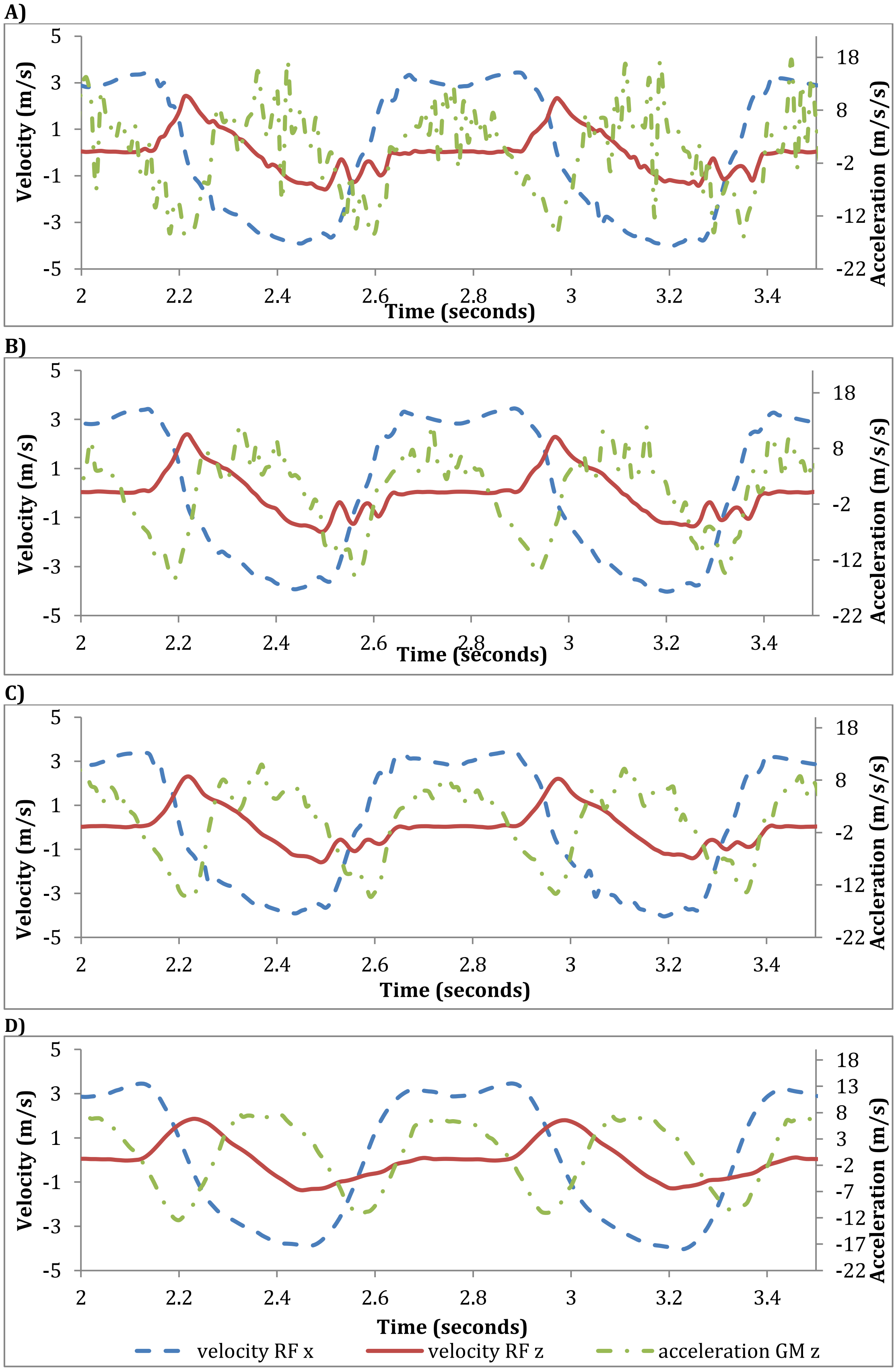


Figure 3: Graphs demonstrating the effects of differing extents of a Savitsky-Golay smoother. (A) no smoother B) 5 point C) 9 point D) 19 point

A nine-point SG smoother was selected as the most effective at preserving trajectory events whilst still smoothing anomalies and data gaps. As *v* and *a* were derived from *p* it was important to ascertain which of these data would require smoothing in the selected way of the many possibilities shown in **Figure 4**.

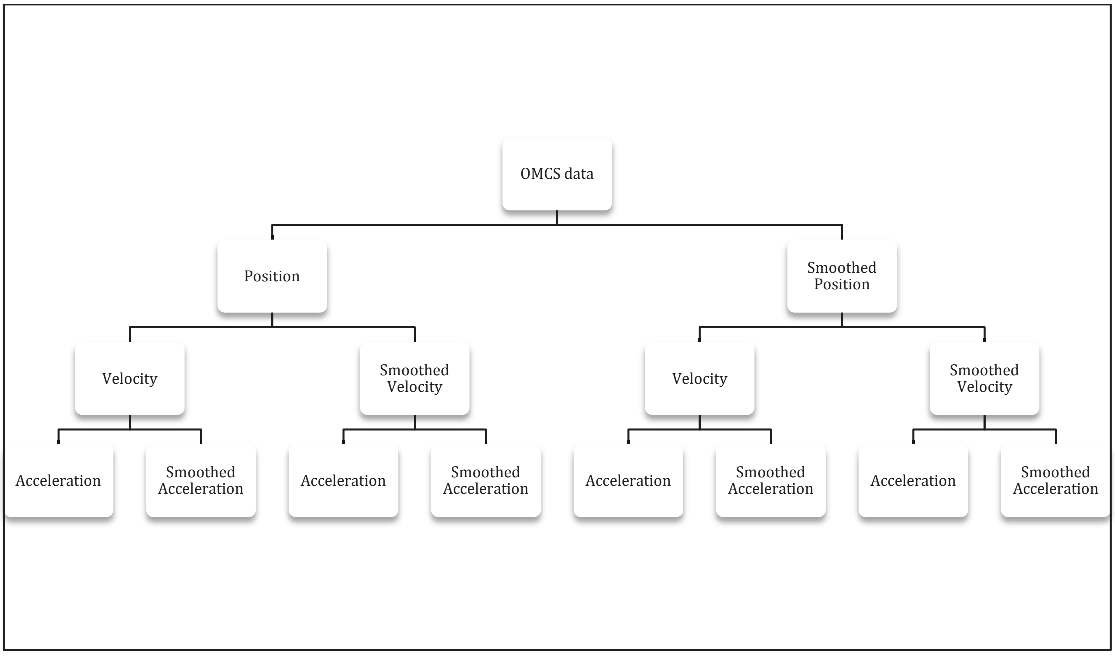
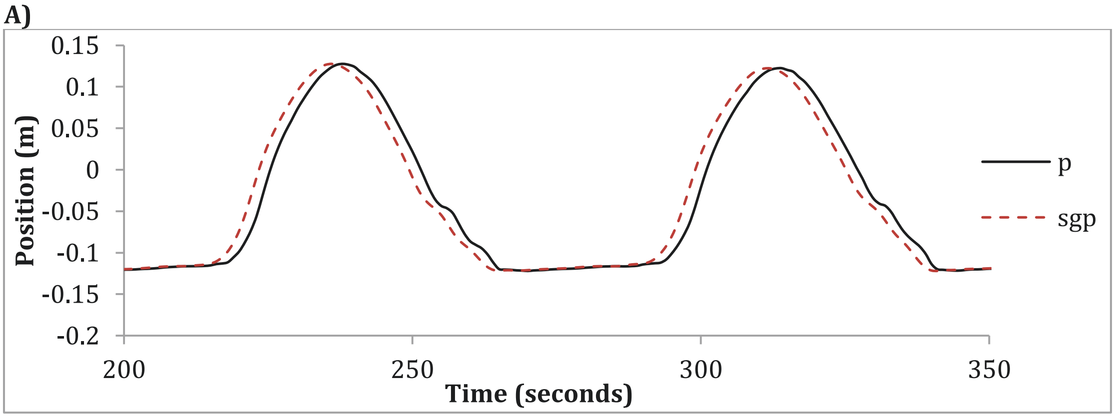


Figure 4: The data stages at which it is possible to implement the smoother.

Therefore, graphs from each of the above derived *a* values were compared as a visual assessment of the amount of detail lost by each of these instants of smoothing, differences in the patterns within each step, and vulnerability to lag. Examples are given in **Figure 5**.

A)



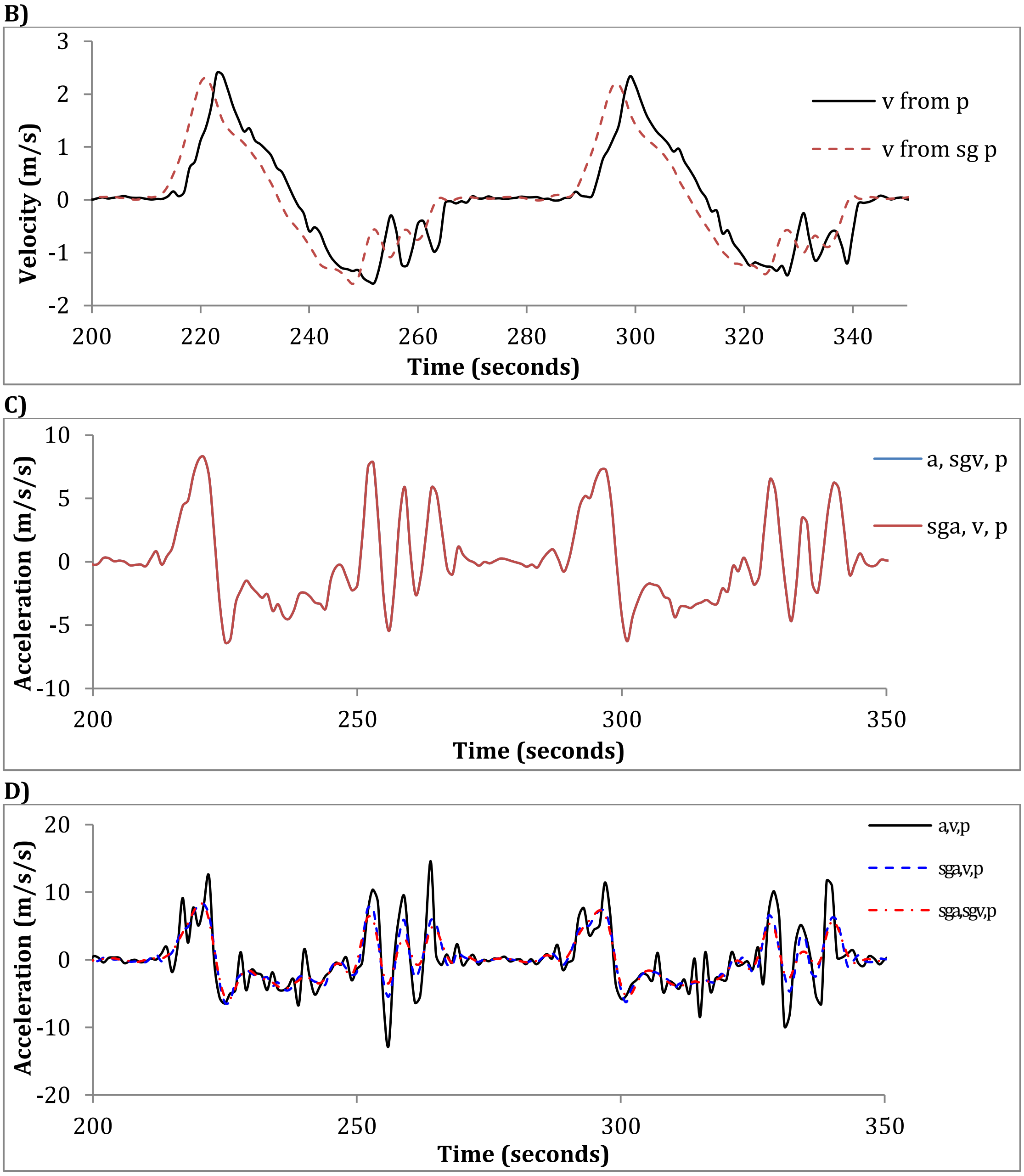


Figure 5: Applying the 9-point SG smoother in position created a time lag effect A), which inevitably was passed on to derivatives such as velocity B). (v = velocity, p = position, and sg p = smoothed position)

C) Applying smoothers at either the velocity or the acceleration phase created identical acceleration graphs. (a = acceleration, sga = smoothed acceleration, v = velocity, sgv = smoothed velocity and p = position)

D) Applying smoothers in the acceleration phase, or in the acceleration and the velocity phase. (a = acceleration, sga = smoothed acceleration, v = velocity, sgv = smoothed velocity and p = position)

It was found that applying the SG nine-point smoother in just *a* preserved significant events, whilst smoothing anomalies and missing data segments, without creating a time lag, whilst applying to both *v* and *a* diminished the clarity of significant events. Thus the 9 point Savitsky-Golay smoother was applied only to *a* of all OMCS data.

2.10.2 IMU

2.10.2.a IMU data processing

IMU measurements are frequently subject to drift as the result of accumulated acceleration. The rotation required to convert data from the object to the global frame often employs an Euler angle matrix (Pfau *et* al., 2005; 2006). But this can result in a loss of data where mathematical gimbal lock becomes an output feature, particularly of angles approximating 90° as Euler rotation matrices rely on basic trigonometry where by cos/sin of 90° = 0 or 1. Whereas quaternion components contain three vectors and one scaler value described in complex numbers that are transferred into a rotation matrix using specific quaternion algebra, thereby avoiding math gimbal and data loss (Esser *et al*., 2009). This system, developed by Oxford Brookes University Movement Science Group was readily available, although horses trotting on a treadmill were not expected to reach angles approximating 90° and thus an Euler system may have sufficed.

Thus, all IMU *a* data was processed in a custom written Labview 20.11 programme using Simpson's rule of integration, using a low pass filter with a cut off of 25Hz, then further de-drifted by DC estimating according to the Hanning Window (whilst deriving *v* and *p* from *a*; and dedrifted by a cubic spline fit, using a balance parameter of 0.9 (non-linear)) (Esser *et al*, 2009).

The IMU gyroscopic rate of turn was processed using Simpson's rule of integration and a direct current (DC) dedrifter applied by DC estimating according to the Hanning Window (and then converted to degrees).

It was aligned so that X = craniocaudal, Y = mediolateral and Z = dorsoventral (see Figure 1).

2.10.2.b Export to Excel

Labelled *a, v* and *p* data were exported as a .tsv file for further handling in Microsoft Excel.

-.3 Synchronisation of IMU and OMCS data

2.10.3.a Base and Extent IMU

In order to be manually synchronized *a*Z of the Base and Extent IMUs were compared (see section **2.4.2**).

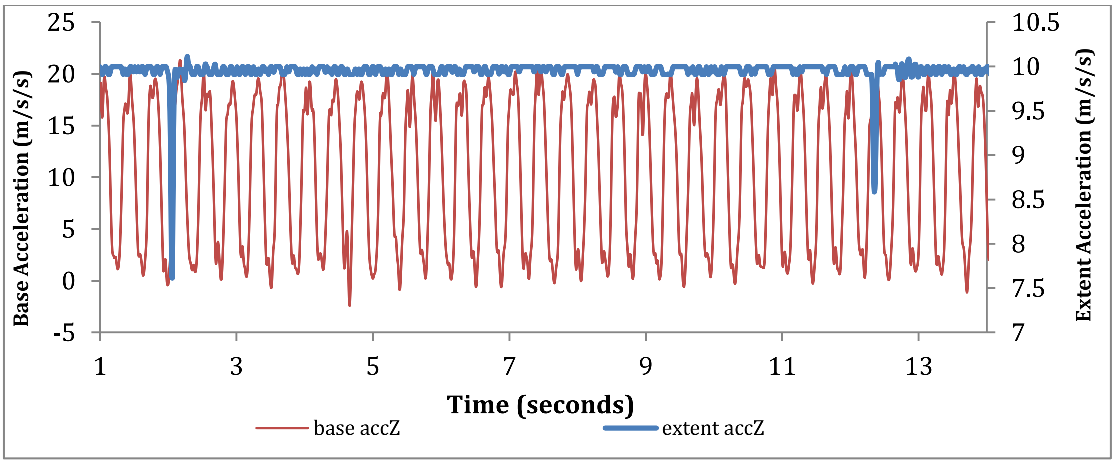


Figure 6: Example graph showing comparison of Base and Extent IMU data.

As can be seen in **Figure 6**, the Extent IMU offered event marking for stride-specific beginning and ending of OMCS measurements, allowing data cutting for comparison with OMCS data.

2.10.3.b Fine adjustment of Base IMU and OMCS

Base IMU *a*Z̲ was then compared with the same data from OMCS. Occasionally the manual methods of synchronization led the signals to be separated by <0.1second, in which case the time difference between the first troughs according to each method was deducted, in order to realign (see **Figure 7**).

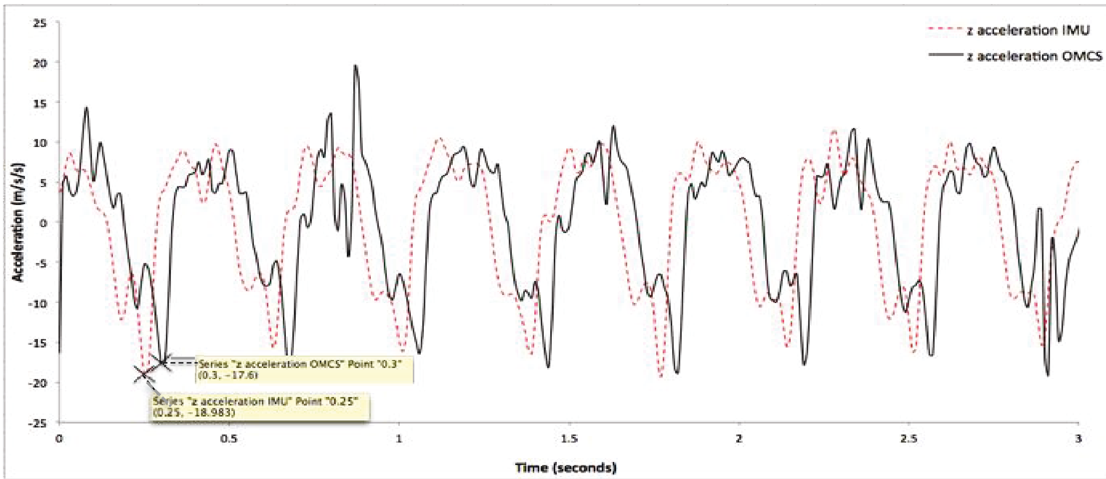


Figure 7: Relationship between Base IMU and OMCS prior to precise synchronisation. In this example graph the difference was 0.05s.

The time difference between OMCS and IMU data being removed (in **Figure 8** the example required the removal of 0.05s of OMCS data), the graphs and data show synchronicity, and the data was ready for analysis.

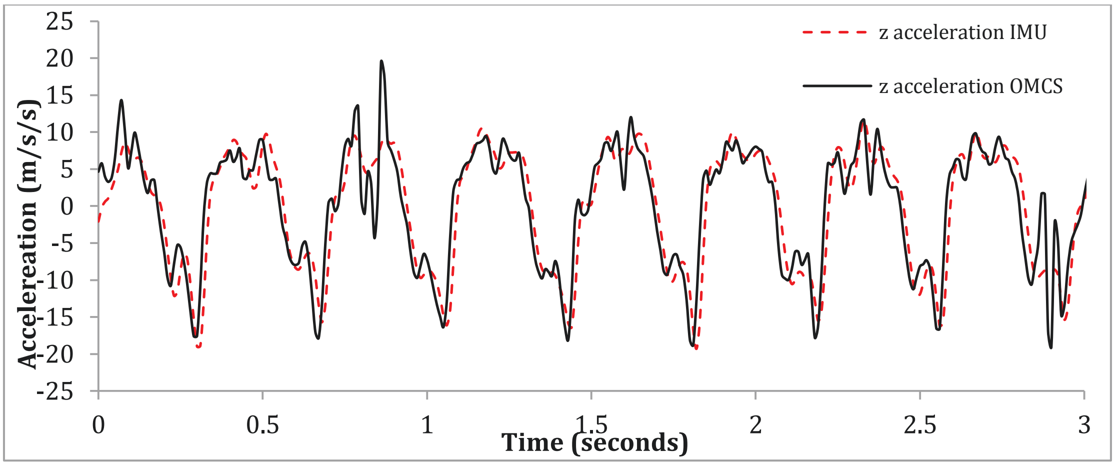


Figure 8: Relationship between Base IMU and OMCS after precise synchronisation. Having removed the 0.05s from the OMCS data, the graph shows synchronicity between OMCS and Base IMU.

2.11 Data Analysis

2.11.1 OMCS hoof trajectory comparison

In order to determine any difference in the methods ascertaining beginning and end of stance from hoof markers, step times were compared between marker trajectories: $v\underline{X}$ (Buchner *et al.*, 1993); $v\underline{Z}$ (Hobbs, *et al*., 2011); and $p\underline{Z}$, by means of a one-way ANOVA and an Intraclass Correlation Coefficient (ICC) 3.1 with absolute agreement.

2.11.2 OMCS contra-laterally coupled hooves comparison

In order to identify any difference between contra-laterally coupled hooves, step times within each diagonal pair (where Right Diagonal = RF and HL; Left Diagonal = LF and HR) were compared at beginning or end of stance (according to $v\underline{X}$) by means of an independent samples t-test for equality of means and ICC test 3.1 with absolute agreement.

2.11.3 OMCS girth marker and hoof marker comparison

The GM traces were visually compared with hoof $v\underline{X}$ to identify events that marked beginning and end of stance of each diagonal. GM $p\underline{Y}$ was assessed for use identifying the forelimb (and thus diagonal) in stance; GM $a\underline{Z}$ and $v\underline{Z}$ were assessed for event identification of beginning and end of stance respectively.

These were compared with hoof $v\underline{X}$ values by means of an independent samples t-test for equality of means and ICC test 3.1 with absolute agreement.

2.11.4 IMU and OMCS Girth Marker

2.11.4.a Diagonal Identification

Percentage agreements of GM and IMU *p*Y̲ and IMU roll were performed to establish the reliability of IMU for identifying the diagonal in stance.

2.11.4.b Peaks

Peak timings of IMU and GM were compared in both *v*Z̲ (greatest peak each step) and *a*Z̲ (first peak each step), by means of both independent sample t-tests for equality of means and ICC test 3.1.

Peak amplitudes of IMU and GM were compared in both *v*Z̲ (greatest peak each step) and *a*Z̲ (first peak each step, by means of both independent sample t-tests for equality of means and ICC test 3.1. IMU and GM, and agreement assessed by means of the Bland-Altman Method.

2.11.4.c Troughs

Trough timings of IMU and GM were compared in both *v*Z̲ and *a*Z̲, by means of both independent sample t-tests for equality of means and ICC test 3.1. IMU and GM.

Trough amplitudes of IMU and GM were compared in both *v*Z̲ and *a*Z̲, by means of both independent sample t-tests for equality of means and ICC test 3.1. IMU and GM, and agreement assessed by means of the Bland-Altman method.

2.11.4.d Amplitudal differences

Agreement between IMU and GM of the extent of amplitudal difference (peak-trough) were compared in both *v*Z (greatest peak) and *a*Z (first peak) by means of the Bland-Altman method.

3 Results

3.1 Subjects

Hartpury College staff selected 16 horses from the yard that matched the inclusion criteria (see section **2.6.**). The horses were a range of breeds, heights, weights and trained to a non-elite level in a range of disciplines (see **Table 3**).

Subject Number	Height (cm) To nearest 0.5cm	Weight (KG)	Breed	Trained Discipline
1	157.5	508	TB	Event
2	167.5	525	Holstein x TB	Event
3	157.5	522	Cob x	SJ
4	165.0	588	WB	All rounder
5	162.5	545	WB	Event
6	165.0	552	ISH	Event
7	165.0	550	ISH	Event
8	165.0	538	ID x	All rounder
9	144.3	492	Pony x	All rounder
10	162.5	561	Dutch WB	SJ
11	170.0	598	WB	SJ
12	172.5	618	Belgian WB	SJ
13	172.0	620	Dutch WB	SJ
14	157.5	518	TB	Event/SJ
15	165.0	541	ISH	Dressage
16	162.5	543	TB x	All rounder

Table 3: Subject attributes of the 16 horses selected for testing.

x = cross bred TB = Thoroughbred WB = Warm Blood ISH = Irish Sports Horse ID = Irish Draught SJ = Show jumper

3.1.1 Subject inclusion

Of the 16 horses selected for testing (see section **3.1**), 15 provided three trials each of OMCS data, and 4 provided three trials each of IMU data (see **Figure 9**).

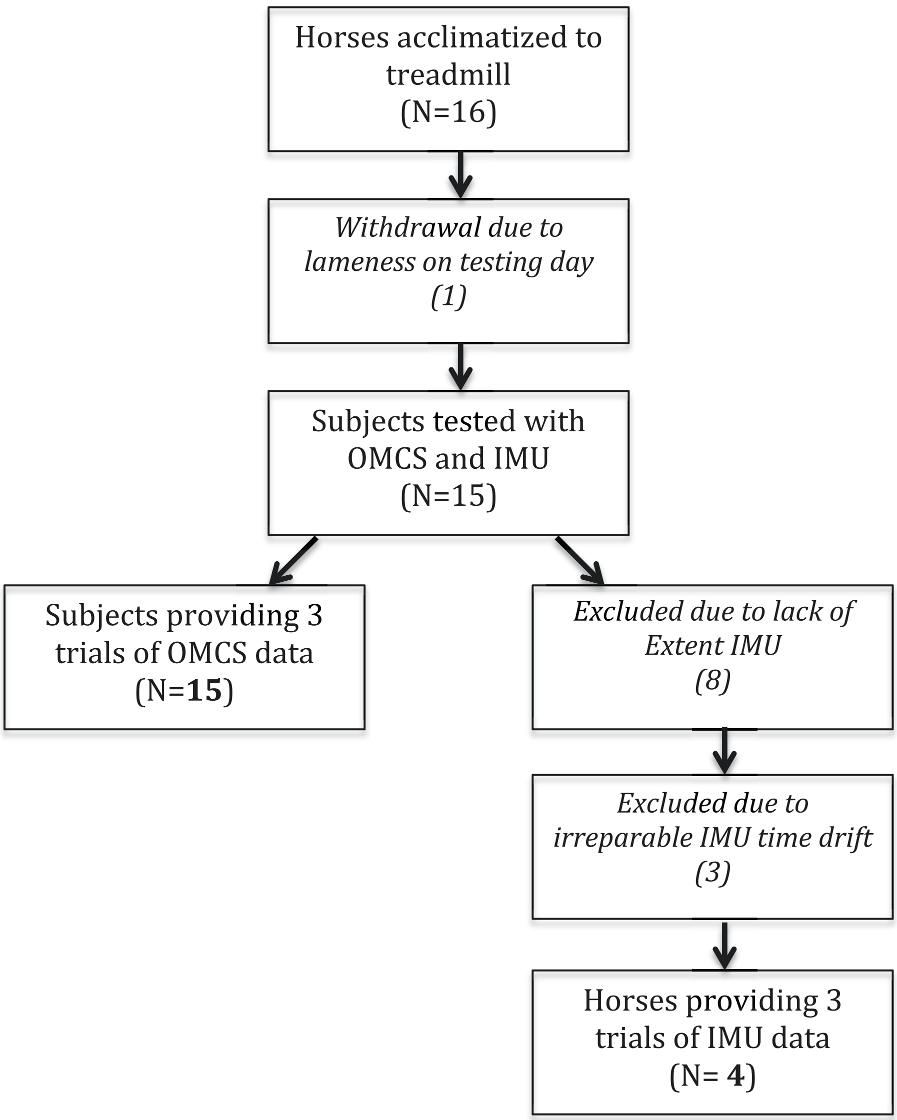


Figure 9: Chart of subject inclusion and progression

3.2 Percentage data fill of OMCS markers

The visibility of markers by cameras varied between marker location and subjects (see **Table 4**). Most consistently measurable was the Girth Marker (GM), whilst the hooves, exhibiting a greater movement were less visible to the camera. However, the latter was only a hindrance if the data missing included beginning or end of stance, which was rare. Spline gap fill was avoided for any single gap consisting of greater than 1% of the total time according to Qualisys Track Manager, because of the inherent danger of a creating a misleading trajectory in larger gaps.

Subject	GM	HR	HL	LF	RF
1	96.4	89.2	27.3	57.5	91.4
2	100.0	98.4	99.8	74.5	99.3
3	100.0	60.2	99.8	89.6	94.6
4	98.3	90.4	72.9	79.1	90.5
5	99.9	88.6	98.8	53.6	1.3
6	100.0	85.0	83.3	49.3	66.8
7	100.0	93.2	94.0	80.7	98.9
8	99.7	85.1	99.9	79.4	98.3
9	100.0	94.8	80.6	53.2	32.4
10	99.8	92.2	90.7	49.2	66.8
11	100.0	91.2	99.9	44.7	56.4
12	100.0	0.0	87.6	83.2	62.6
13	100.0	92.4	99.8	41.0	38.6
14	100.0	71.5	96.6	62.3	67.9
15	100.0	70.3	87.3	45.5	73.3

Table 4: Percentage data fill of OMCS markers, averaged across trials in each subject.

3.3 IMU Lack of Extent

Nine of the subject tests provided no Extent IMU data. (The Extent IMU was placed on a stable surface next to the receiving laptop and tapped in order to aid synchronization of the Base IMU attached to the horse's *sternum*, see sections **2.4.2** and **2.10.3**). This made synchronization of the Base IMU and QTM too complex to be truly reliable, and Base IMU data from these subjects was therefore excluded from the results comparing IMU with QTM. However, the results still proved useful for investigating the IMU time drift.

3.3.1 IMU Time drift

It was noted on synchronization of IMU with QTM that a time discrepancy occasionally appeared, and increased in both occurrence frequency and deviation with the increase of time passing within the trial (see **Figure 10**).

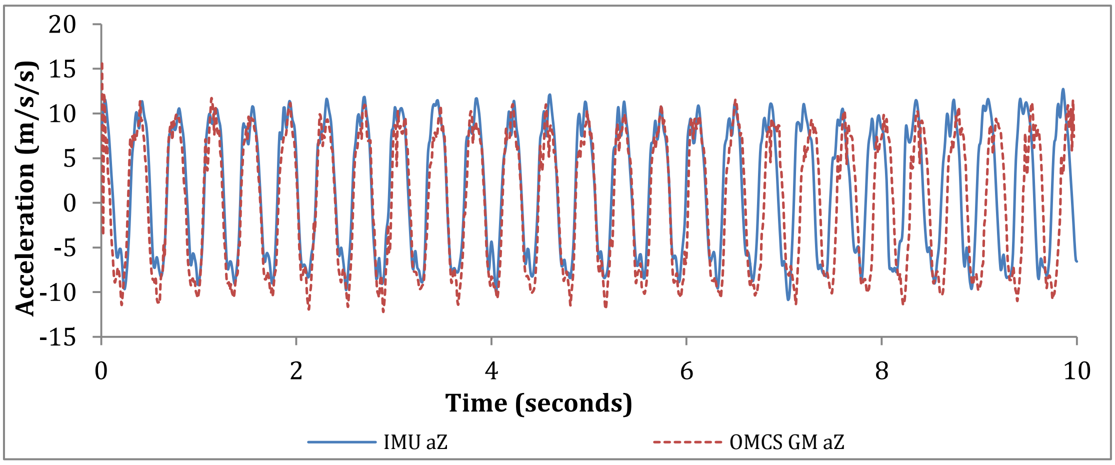


Figure 10: Example graph showing the time drift in the IMU

Upon investigation, this discrepancy was found to occur in accordance with a time stamping issue on the IMU data. Data should be measured at 100Hz (every 0.01second) and be packaged into groups of four measurements for Bluetooth transfer to the receiving computer. It is an acceptable margin of error that on these 'package transfers' the time difference is not precisely 0.01s after the previous measurement, but might instead be 0.008-0.012 seconds after. However, on close inspection of every single data packet some less acceptable time differences were noted. These ranged from gaps as large as 0.09 seconds to an impossible -0.009 seconds. The frequency of these time lags was also of concern: of 15 horses each providing three trials, only two trials in total did not contain at least one data packaging issue (<0.008s or >0.02s). One trial contained a total of 15 erroneous packages. There were an average 6.13 errors in each trial.

In order to establish the cause of the errors, the number of packaging errors in single (Base) IMU trials was compared with the number in double (Extent and Base) IMU trials. It was found that in the 24 trials (from 8 subjects) with only a Base IMU, there were a total of 60 errors, demonstrating an average 2.5 errors per trial. However, in the trials using both an Extent and Base IMU, the likelihood of error more than quadrupled, with a total of 216 errors across the 21 trials (from 7 subjects), and an average of 10.29 errors per trial. Furthermore, of the 216 errors, 98 of them (45.37%) coincided in both Extent and Base IMUs simultaneously.

Considering that the IMUs do not intercommunicate, and that their different positioning make it unlikely that interference (such as magnetism from the treadmill) would occur in both at the same time, the most likely explanation for the time packaging issues is a communication error between the IMUs and the laptop receiver, and not with the data measurement itself (confirmed by personal communication with Dax Steins 2014 MSG electronics specialist).

Confident, therefore, that the measurements themselves were unhindered and only the time stamp was at fault, each error was rectified by eliminating the data at each occurrence. An accurate time stamp was then created and a new acceleration data point by smoothing the gap between previous and subsequent. This technique eliminated time lag drift and was possible across all trials in four of the seven subjects.

3.4 OMCS Hoof trajectory comparison

In order to investigate H_1 (see section **1.8**) step times were compared according to hoof marker trajectories *v*X, *v*Z, and *p*Z as shown in **Figure 11.**

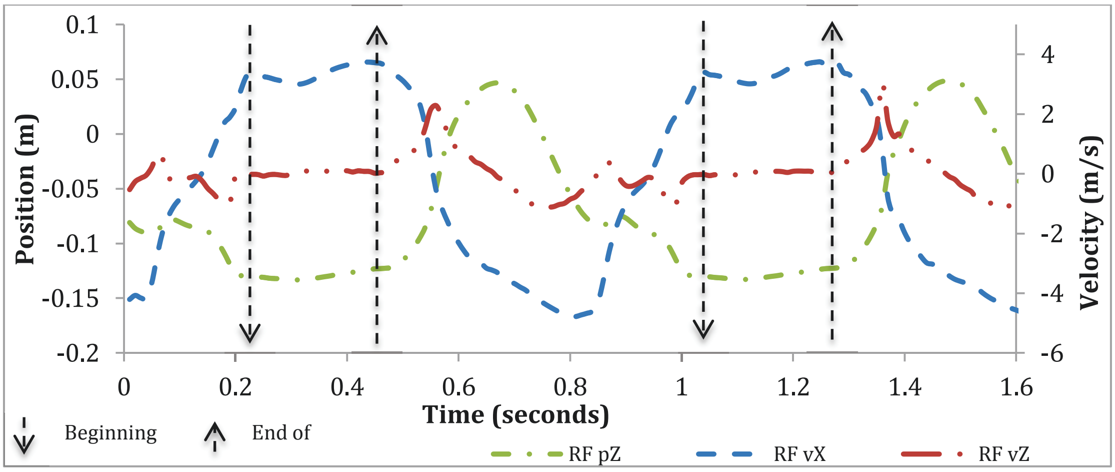


Figure 11: Beginning and end of stance of Right Fore (RF) according to trajectories *p*Z, *v*X, and *v*Z.

The one-way ANOVA performed to assess any difference between the three stance timing measurement techniques (hoof trajectories *v*X, *v*Z, and *p*Z) revealed no significant difference at the $p < .05$ level [$F(2,507) = .002$, $p=.998$].

Similarly, the ICC performed to assess the variance of these same techniques also revealed no difference [ICC 1 (95%CI: 1-1).

3.5 OMCS contra-laterally coupled hooves comparison

In order to investigate H_2 (see section **1.8**) contra-laterally coupled hooves were compared at beginning and end of stance by *v*X of each hoof.

	Time (seconds)							
	HL Beginning of stance	HL End of stance	HR Beginning of stance	HR End of stance	RF Beginning of stance	RF End of stance	LF Beginning of stance	LF End of stance
Mean	0.74	0.75	0.75	0.75	0.75	0.74	0.75	0.74
Max	0.83	0.84	0.82	0.83	0.82	0.83	0.89	0.83
Min	0.60	0.63	0.66	0.66	0.59	0.61	0.66	0.66
N	163	172	183	182	160	173	151	173

Table 5: Mean, Maximum and Minimum step times according to hoof markers of 15 horses.

N = the number of these events identifiable in the signal of the relevant marker (variable between markers due to varying amounts of missing data): HL = Hind Left, HR = Hind Right, RF = Right Fore, LF = Left Fore.

Beginning of stance timings for the Right Diagonal according to RF or HL were not significantly different according to the t-test at the p< .05 level *t* (321) = -0.029, p= 0.77 (95% CI: -0.02 – 0.1), nor was the variance significant according to the ICC 0.93 (95% CI: 0.90 – 0.95).

Beginning of stance timings for the Left Diagonal according to LF or HR were not significantly different according to the t-test at the p< .05 level *t* (332) = -0.06, p=0.95 (95% CI: -0.01 – 0.01), nor was the variance significant according to the ICC 0.81 (95% CI: 0.74 – 0.86).

End of stance timings for the Right Diagonal according to RF or HL were not significantly different according to the t-test at the p< .05 level *t* (343) = 0.52, p = 0.60 (95% CI: -0.01 – 0.01, nor was the variance significant according to the ICC 0.74 (95% CI: 0.65 – 0.80).

End of stance timings for the Left Diagonal according to LF or HR were not significantly different according to the t-test at the p< .05 level *t*

(353) = 0.74, p = 0.46 (95% CI: -0.01 – 0.01), nor was the variance significant according to the ICC 0.75 (95% CI: 0.68 – 0.81).

3.6 Diagonal Identification from GM

In accordance with H_4 (see section **1.8**), and as shown in **Figure 12** GM *p*Y indicated which forelimb (and diagonal) was in stance: a peak indicating the right, and a trough to the left.

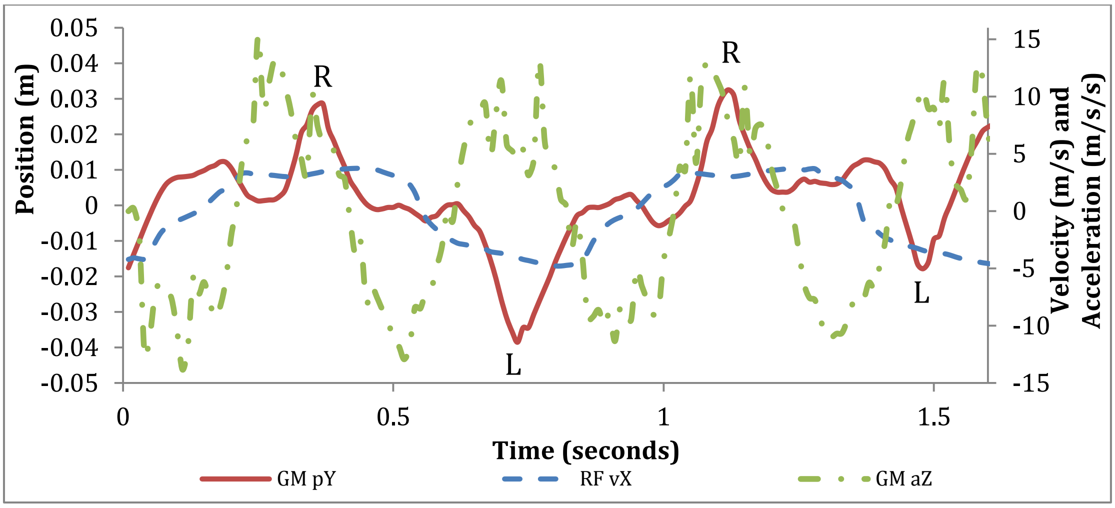


Figure 12: Comparison of Right Fore (RF) *v*X and Girth Marker (GM) *a*Z with GM *p*Y indicating which diagonal is in stance.

Right diagonal (R) = Right Fore and Left Hind. Left diagonal (L) = Left Fore and Right Hind.

3.7 Beginning of Stance from GM

In accordance with H_3 (see section **1.8**) the first peak of GM *a*Z after the trough coincided with beginning of stance according to hoof *v*X, as shown in **Figure 13**.

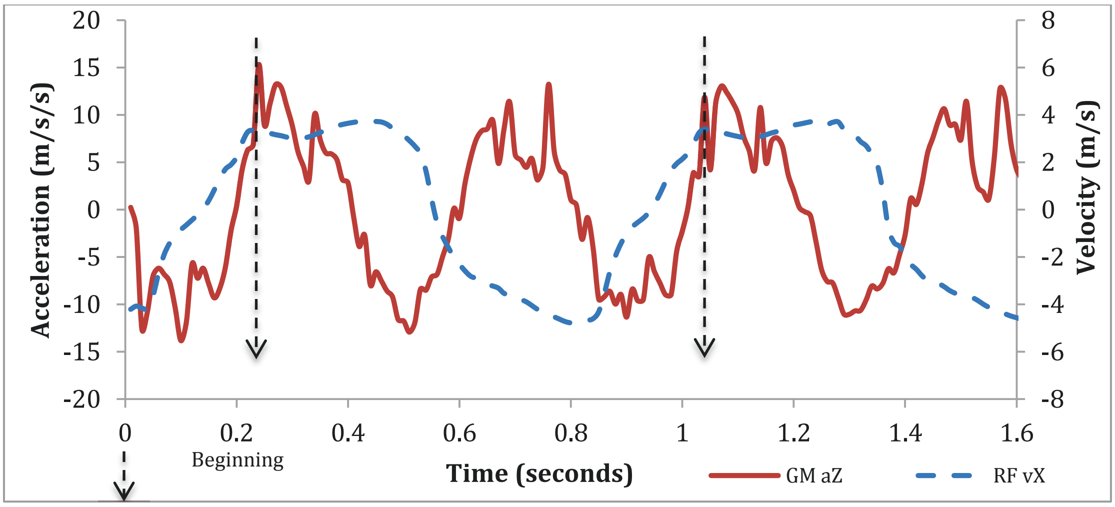


Figure 13: The first peak after the trough of Girth Marker (GM) *a*Z coincided with beginning of stance according to vX of Right Fore (RF)

(The recurring GM pattern, which alternately corresponds with the events of RF; the other corresponds with the Front Left, but is not shown for the sake of clarity.)

GM *a*Z was then used (whilst blinded to hoof *v*X) to delineate beginning of stance for all strides in all samples (see **Table 6**).

	Step Time (seconds)	
	Left Diagonal beginning of stance from GM	Right Diagonal beginning of stance from GM
Mean	0.75	0.75
Max	0.85	0.85
Min	0.65	0.65
N	189	189

Table 6: Beginning of stance of each diagonal according to Girth Marker (GM).

Right Diagonal = Right Fore and Hind Left. Left Diagonal = Left Fore and Hind Right.

Beginning of stance timings for the right diagonal according to hoof or GM were not significantly different according to the t-test at the $p < .05$ level t (335) = -0.069, p=0.49 (95% CI: -0.01 – 0.01), nor was the variance significant according to the ICC 0.59 (95% CI: 0.48 – 0.68).

Beginning of stance timings for the left diagonal according to hoof or GM were not significantly different according to the t-test at the $p < .05$ level t (352) = -0.11, p=0.91 (95% CI: -0.01 – 0.01), nor was the variance significant according to the ICC 0.63 (95% CI: 0.53 – 0.71).

3.8 End of Stance from GM

In accordance with H_3 (see section **1.8**) the highest peak of GM *v*Z was found to coincide with end of stance according to hoof *v*X as shown in **Figure 14.**

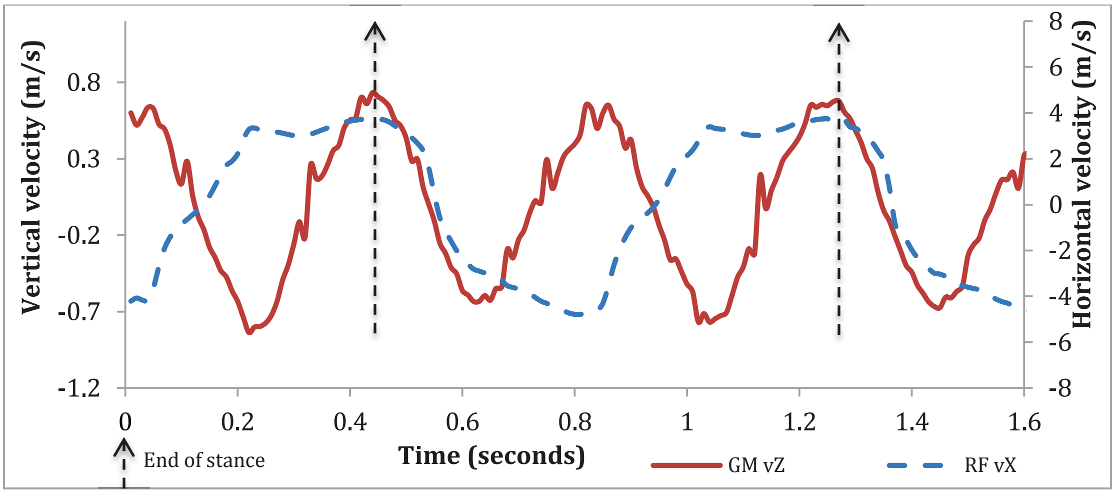


Figure 14: The highest peak of Girth Marker (GM) *v*Z was found to coincide with end of stance according to *v*X of Right Fore (RF)

(The recurring GM pattern, which alternately corresponds with the events of RF; the other corresponds with the Front Left, but is not shown for the sake of clarity.)

GM *v*X was then used (whilst blinded to hoof *v*X) to delineate end of stance of all strides in all samples (see **Table 7**).

	Step Time (seconds)	
	Left Diagonal from GM end of stance	Right Diagonal from GM end of stance
Mean	0.74	0.74
Max	0.84	0.83
Min	0.67	0.66
N	187	186

Table 7: End of stance of each diagonal according to Girth Marker (GM).

Right Diagonal = Right Fore and Hind Left. Left Diagonal = Left Fore and Hind Right.

End of stance timings for the right diagonal according to hoof or GM were not significantly different according to the t-test at the $p < .05$ level t (370) = 0.20, p=0.84 (95% CI: -0.01 – 0.01), nor was the variance significant according to the ICC 0.74 (95% CI: 0.67 – 0.80).

End of stance timings for the left diagonal according to hoof or GM were not significantly different according to the t-test at the $p < .05$ level t (370) = 0.21, p=0.83 (95% CI: -0.01 – 0.01), nor was the variance significant according to the ICC 0.59 (95% CI: 0.48 – 0.68).

3.9 GM OMCS and IMU comparison

3.9.1 Diagonal Identification

As postulated by H_4 (see section **1.8**) identification of the diagonal in stance was possible by means of IMU or OMCS position, or IMU roll (Starke *et al*., 2012). Derived $p\underline{Y}$ from IMU had 97% agreement with that from OMCS; disagreement referred to lack of clarity, rather than incorrect identification. IMU roll had 100% agreement with diagonal identification according to OMCS GM $p\underline{Y}$.

3.9.2 Peaks

In order to partly investigate H_5 (see section **1.8**), GM and IMU velocity and acceleration peaks were determined both in terms of timings and amplitude (see **Table 8**).

	Mean	Standard Deviation	N
Velocity Peak Timing OMCS (seconds)	3.23	1.96	204
Velocity Peak Amplitude OMCS (m/s)	0.58	0.08	204
Acceleration Peak Timing OMCS (seconds)	3.16	1.96	204
Acceleration Peak Amplitude OMCS (m/s/s)	9.10	3.06	204
Velocity Peak Timing IMU (seconds)	3.23	1.96	204
Velocity Peak Amplitude IMU (m/s)	0.57	0.09	204
Acceleration Peak Timing IMU (seconds)	3.17	1.96	204
Acceleration Peak Amplitude IMU (m/s/s)	8.5	2.06	204

Table 8: Peak timings and amplitudes according to OMCS and IMU data.

3.9.2.a Timings

Timings of velocity peaks according to OMCS and IMU were not significantly different according to the t-test at p< .05 level *t* (406) = 0.01, p = 0.99, (95% CI: -0.37 – 0.38), nor was the variance significant according to ICC 1.00 (95% CI: - 1.00 – 1.00).

Timings of acceleration peaks according to OMCS and IMU were not significantly different according to the t-test at p< .05 level *t* (406) = 0.04, p = 0.97, (95% CI: -0.37 – 0.39), nor was the variance significant according to ICC 1.00 (95% CI: -1.00 – 1.00).

3.9.2.b Amplitudes

Amplitudes of velocity peaks according to OMCS and IMU were not significantly different according to the t-test at p< .05 level *t* (406) = -0.57, p = 0.12, (95% CI: -0.30 – 0.00), nor was the variance significant according to ICC 0.89 (95% CI: 0.86 – 0.91).

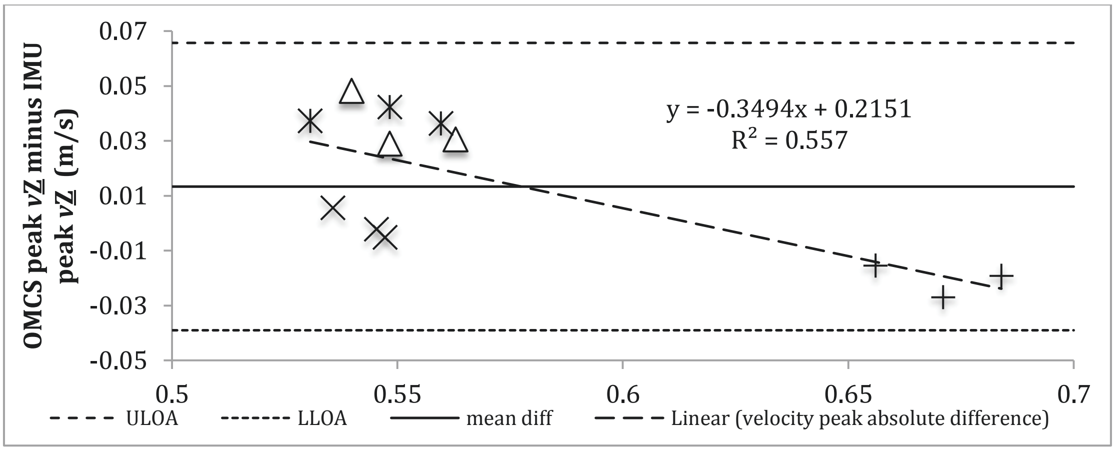


Figure 15: Bland Altman plot demonstrating the relationship between IMU and OMCS at peak vertical velocity

Amplitudes of acceleration peaks according to OMCS and IMU were significantly different according to the t-test at p< .05 level t (356) = -2.47, p = 0.01, (95% CI: -1.14 – -0.13), the variance was also significant according to ICC 0.46 (95% CI: 0.35 – 0.57).

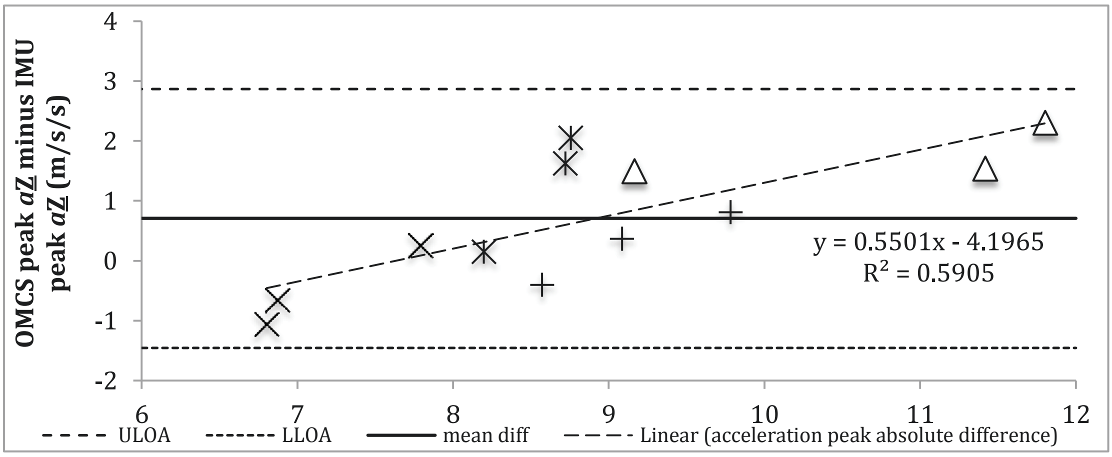


Figure 16: Bland Altman plot demonstrating the relationship between IMU and OMCS at peak vertical acceleration

3.9.3 Troughs

In order to further investigate H_5 (see section **1.8**), GM and IMU acceleration troughs were determined both in terms of timings and amplitude (see **Table 9**).

	Mean	Standard Deviation	N
Velocity Trough Timing OMCS (seconds)	3.09	1.97	204
Velocity Trough Amplitude OMCS (m/s)	-0.62	0.06	204
Acceleration Trough Timing OMCS (seconds)	3.21	1.96	204
Acceleration Trough Amplitude OMCS (m/s/s)	-13.80	2.96	204
Velocity Trough Timing IMU (seconds)	3.09	1.96	204
Velocity Trough Amplitude IMU (m/s)	-0.62	0.07	204
Acceleration Trough Timing IMU (seconds)	3.21	1.96	204
Acceleration Trough Amplitude IMU (m/s/s)	-13.65	2.61	204

Table 9: Trough timings and amplitudes according to OMCS and IMU data.

3.9.3.a Timings

Timings of velocity troughs according to OMCS and IMU were not significantly different according to the t-test at $p < .05$ level t (406) = -0.00, p = 0.99, (95% CI: -0.38 – 0.38), nor was the variance significant according to ICC 1.00 (95% CI: - 1.00 – 1.00).

Timings of acceleration troughs according to OMCS and IMU were not significantly different according to the t-test at $p < .05$ level t (406) = 0.04, p = 0.97 (95% CI: -0.37 – 0.39), nor was the variance significant according to ICC 1.00 (95% CI: -1.00 – 1.00).

3.9.3.b Amplitudes

Amplitudes of velocity troughs according to OMCS and IMU were not significantly different according to the t-test at $p < .05$ level t (406) = 0.29, p = 0.77, (95% CI: -0.01 – 0.01), nor was the variance significant according to ICC 0.87 (95% CI: 0.83 – 0.90).

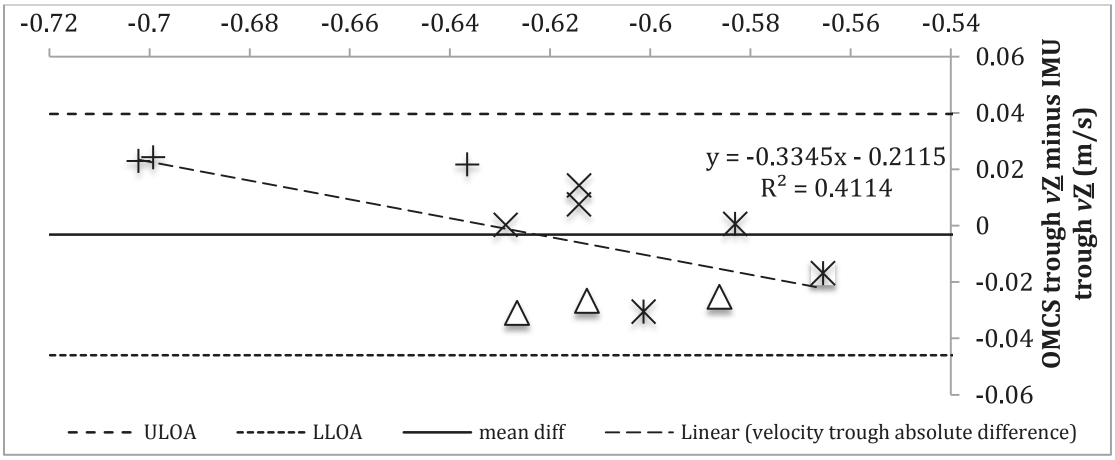


Figure 17: Bland Altman plot demonstrating the relationship between IMU and OMCS at the vertical velocity troughs

Amplitudes of acceleration troughs according to OMCS and IMU were not significantly different according to the t-test at p< .05 level *t* (406) = 0.56, p = 0.58, (95% CI: -0.39 – 0.70), nor was the variance significant according to ICC 0.82 (95% CI: 0.76 – 0.86).

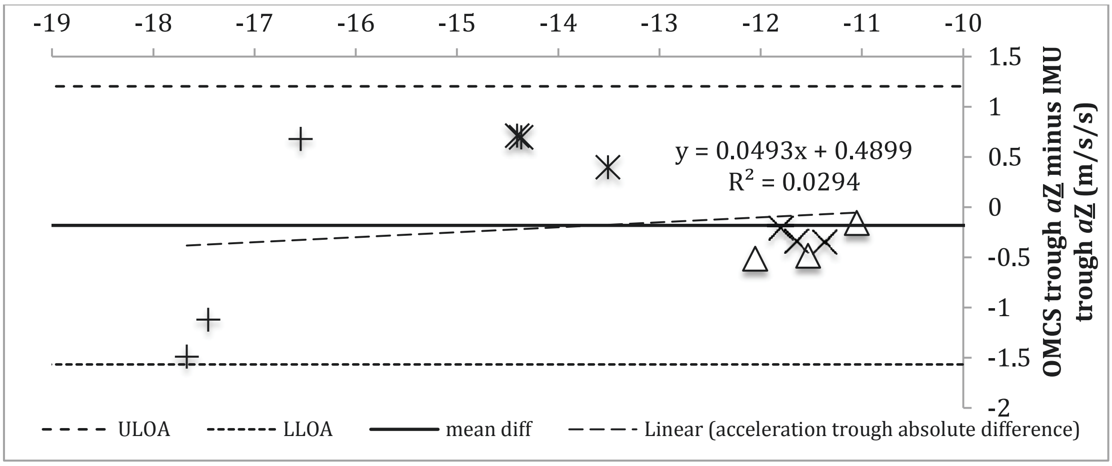


Figure 18: Bland Altman plot demonstrating the relationship between IMU and OMCS at vertical acceleration troughs

3.9.4 Amplitudal Differences

In order to further investigate H_5 (see section **1.8**), IMU and QTM measurements were also determined by means of amplitudal difference between peak and trough (see **Table 10**).

	Mean	Standard Deviation	N
Velocity peak minus trough OMCS (m/s)	3.09	1.97	204
Velocity peak minus trough IMU (m/s)	3.09	1.96	204
Acceleration peak minus trough OMCS (m/s/s)	22.90	4.25	204
Acceleration peak minus trough IMU (m/s/s)	22.12	3.38	204

Table 10: Amplitude differences (peak minus trough) of velocity and acceleration according to OMCS and IMU data.

The differences (peak minus trough) of velocity amplitudes were not significantly different *t* (387) = -1.2, p = 0.25 (95% CI: -0.04 – 0.01) ICC=0.89 (95% CI: 0.85 – 0.91).

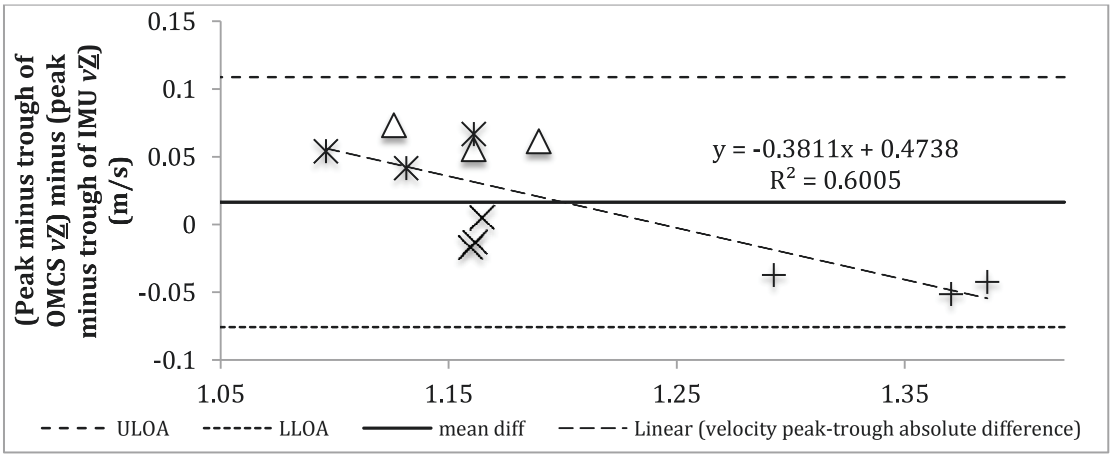


Figure 19: Bland Altman plot demonstrating the relationship between IMU and OMCS in terms of amplitudal difference (peak minus trough) of vertical velocity

However the differences (peak minus trough) of acceleration amplitudes were significantly different t (387) = -2.1, p = 0.04, (95% CI: -1.54 – -0.04), ICC=0.66 (95% CI: 0.57 – 0.73).

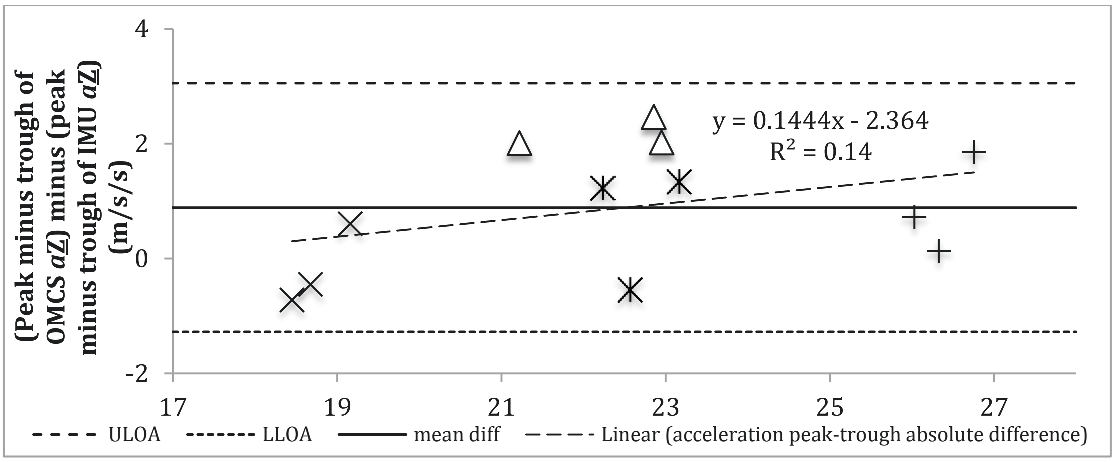


Figure 20: Bland Altman plot demonstrating the relationship between IMU and OMCS in terms of amplitudal difference (peak minus trough) of vertical acceleration

4 Discussion

The results of this study show that the measurements from the *sternum* using either OMCS or an IMU can be used to identify beginning and end of stance of each diagonal for horses trotting on a treadmill. This site proved less vulnerable to OMCS marker obscuring than hoof markers, and the use of the girth for attachment makes it a convenient, anatomically stable location to which riding horses are already desensitised. IMU data were not significantly different from OMCS GM data at peak or trough timings in velocity or acceleration, peak or trough amplitude in velocity, or trough amplitude in acceleration. However the differences at peak amplitude in acceleration, and the time stamp issues (although correctable) lead to the requirement of caution when inferring gait characteristics from unchecked IMU data.

4.1 OMCS

The mean percentage fill of the hoof markers within each trial was 66.1% (range: 1.3 – 99.3%) for the forelimbs, and 84.0% (range: 0 – 99.9%) for the hind limbs. Marker concealment and loss is a known disadvantage of OMCS systems and given the relatively large trajectories taken by equine limbs the large measuring volume creates a greater potential for error. The lower percentage fill for the forelimbs than hindlimbs is perhaps due to the presence of the handlers holding the lead reins by the head (though efforts were made to remain unintrusive). The girth at the *sternum* has not (to the author's knowledge) been used as a site for an OMCS marker before this study, and was found to have a more consistent visibility to cameras placed in the way described, with a mean percentage fill of 99.6% (range: 96.4 – 100%). This is perhaps due in part to the smaller trajectory taken by this location in comparison to the hooves, and also to the straightness of the horse enforced by the treadmill surround; whether percentage fill would remain so high overground is worth investigating.

In comparing different outputs of the hoof trajectory ($v\underline{X}$, $v\underline{Z}$, and $p\underline{Z}$) no significant difference or variance was found by the ANOVA or ICC thus allowing the acceptance of H_1 (section **1.8**). Various methods have been used in other studies for identifying stance and swing, the one used in this study is most similar to that presented by Buchner *et al.* (1993) in which overground stance < $v\underline{X}$ 0.1m/s > swing, but with alterations for constant hoof movement by the treadmill belt. One method for identifying beginning of stance uses $v\underline{X}$ and $a\underline{Z}$ for the fore and hind limbs respectively. It was validated in overground trot (Olsen *et al*., 2012) against a forceplate with a threshold of 10N. According to the findings of Olsen *et al*. (2012) $a\underline{X}$ and $p\underline{X}$ were recommended for the identification of end of stance of fore and hind limbs respectively ($p\underline{X}$ used here at the cannon may be distorted by pitch rotation if attempted from the hoof). Since testing, Boye *et* al. (2014) published data comparing five methods employed by different papers, and (for OMCS measuring overground trot) recommended $v\underline{X}$ and $a\underline{Z}$ for beginning and end of stance respectively, according to overall precision, accuracy and consistency compared to a force plate. Witte *et al*. (2004) recommended the use of $a\underline{Z}$, as was validated against a forceplate in horses walking and trotting overground with a threshold of 50N, and this method has consequently been used in other studies (e.g., Starke *et al.*, 2012). However, this quite large threshold (50N) may exclude the hoof slip feature found to be a potentially large (mean 4.39cm on wet sand) contributor to the stance phase (Holden Douilly *et al.,* 2013). Conversely influence of surface must also be considered, with those of high friction (such as rubber) and more especially the counter movement of the treadmill belt most likely to reduce hoof slip. Leleu *et al.* (2002) defined the beginning of stance using a videographic system as the last image before any distal extension of the fetlock; this is likely to preclude much of the hoof slip from stance and also employs a 2D system at some distance from the track that may limit its sensitivity. Leleu *et al.* (2002) also defined end of stance as the last image in which the toe was in contact with the ground, by which time the hoof has undertaken pitch rotation and has was not weight bearing previous to this point. Hooves also rotate in the roll and yaw planes at end of stance and these would have been invisible to the 2D videographic system.

Given that none of the compared trajectories showed any significant difference from one another and have previously been validated overground, the *v*X̲ seemed sufficiently reliable for the purposes of this study. Given the rarity of forceplate-embedded equine treadmills, more thorough comparison of these techniques against a gold standard method was not possible in this study.

No significant difference was found by t-test or ICC at beginning or end of stance between each fore and their contra-laterally coupled limbs. This lead to the acceptance of H_2 (see section **1.8**) that there was no evidence of advanced hindlimb placement according to OMCS hoof trajectories in unridden horses trotting at self-selected speeds on a treadmill.

Although trot is loosely defined as the coupling of contra-laterally coupled limbs in this way, advanced diagonal placement has been found in some studies. Clayton *et al*. (1997) found that 10 horses placed in the top 12 for dressage at the 1992 Olympics showed advanced hindlimb placement for collected and passage trot, with higher placed horses showing a greater degree of dissociation. In the same study piaffe showed advanced forelimb placement across horses, with a smaller difference being evident in the highest ranked horses. No significant difference was found at end of stance in any of the conditions.

The degree of dissociation from advanced hindlimb placement in dressage bred horses at the overground working trot has been found to be significantly higher in trained than untrained animals, and higher in ridden than led animals (Morales *et al*., 1998). The degree of advanced placement (fore or hindlimb) has also been shown to alter significantly with head carriage (a result of training and accurate riding) of elite dressage horses (Weishaupt *et al*., 2006).

Conversely, Standardbred trotters tend to demonstrate advanced forelimb placement and lift off, with the length of dissociation being greater at lift off, and being asymmetrical in 25% of compared diagonals (Drevemo *et al*., 1980).

Buchner *et al*. (1994, *a*) investigated such differences between overground and treadmill exercise and found advanced placement in both conditions; hindlimb overground and forelimb on a treadmill. This could partly be due to the counter movement of the treadmill encouraging a double rather than single stance, and also could have been influenced by the horses being ridden overground and led on the treadmill (Morales *et al.*, 1998).

Theoretically, the elevation and balance required for dressage would be aided by an increased hind limb stance duration, which may explain the advanced hind limb placement in elite members of this discipline. The advanced forelimb placement in trotters may allow the greater degree of impact forces to be absorbed by the soft tissues of the chest, and the advanced forelimb lift off allow hind limbs to propel without resistance from forelimb contact.

Considering the effects of a treadmill cannot be separated from the effects of a rider (Buchner *et al.*, 1994 *b*). It remains unknown whether the non-elite, discipline non-specific horses in the current study would have shown advanced placement of one sort or another had they been trotted overground. If such dissociation had been detectable, it would have been interesting to investigate whether it was possible to identify and analyse it from the *sternum* alone or whether using both the *sternum* and the *os sacrum* allowed clearer measurements.

The diagonal in stance was identifiable by OMCS GM or IMU *p*Y̲ or by IMU roll. This supported the acceptance of H_4 (see section **1.8**), that the diagonal in stance was detectable by both OMCS and IMU from the sternum. Roll of an *os sacrum* mounted IMU has been used to identify hindlimbs in stance during overground locomotion (walk and trot on a straight line and a circle) by Starke *et al*. (2012), and the results were consistent with those presented in this study and were also proved to be robust in lame horses. To the author's knowledge investigation of *p*Y of the *sternum* had not been investigated by previous work, possibly due to its lack of prior investigation as a site for OMCS measurement.

4.2 IMU validity

The time drift found in this study created potential problems for IMU data collection. It is recommended that in future investigators check the time stamp of all data files before proceeding to analysis, as the findings could be misleading.

One study investigating the use of MP3 recorders to collect accelerometer data also found time drift (Parsons *et al*, 2006). The study comprised three experiments, the first compared data from each hoof of six ridden horses walking and trotting on tarmac and a sand arena for 30 minutes, continuously logged by an MP3 recorder on the cannon of each limb. A pulse was imposed on the data describing beginning and end of the sample. The relationship between accumulated error of the data sources and time was examined. An average of ten errors were found in 106 samples (1000Hz), or 10ms error over 17 minutes of recording. There was a strong correlation ($r = 1.0$, $p \leq 0.01$) between absolute error from each MP3 recorder and time interval between pulses. A second experiment in the same study compared data logged from a left fore hoof accelerometer by a laptop, with the same analogue data sent continuously to an MP3. Beginning and end of stance times were extracted according to Witte *et al*. (2004) and comparison between the two logging systems revealed a mean (standard deviation) of 3.07 (4.17) ms at beginning of stance and 3.94 (3.39) ms at end of stance at trot, where data logged by the laptop was assumed to be the true value.

This data supports the findings of the current study that time drift issues can occur during IMU data logging. However, the assumption of the Parsons *et al* (2006) study that data logged by a laptop the true value is contradicted by the findings presented here, where discrepancies were found despite laptop collection; it is suggested that laptop logging can still cause timing issues, although MP3 logging may exaggerate the error further. Conversely, in the MP3 *versus* laptop logging comparison undertaken by Parsons *et al* (2006), only one accelerometer was logging data per trial. The fact in the present study occurrence of error increased fourfold with trials employing two IMUs suggest that researchers collecting synchronous data from separate IMU sites (such as *sternum* and *os sacrum*, or hooves) have particular reason to be vigilant to this error. With the error identified it is relatively straightforward to correct, and the correlation of error with time over continuous sampling found by Parsons *et al* (2006) can be corrected by splitting the data in the methods described in the current study.

This time lag error could have been more effectively investigated by either logging IMUs to separate computers, although this would have made synchronization of the systems more complicated; or by using wired IMUs (logging to a laptop rather than MP3 recorder due to the concerns raised by Parsons *et al*., 2006). However, this study was initially set out to be a precursor to overground work, where wired connection to a laptop requires the latter to be connected to the horse, rider or sulky.

The timings of $a\underline{Z}$ and $v\underline{Z}$ peaks and troughs according to OMCS and IMU in the current study showed no significant difference, with impressive ICCs of a unanimous 1.00 (95% CI: -1.00 – 1.00). Amplitudes of $a\underline{Z}$ and $v\underline{Z}$ troughs as well as $v\underline{Z}$ peaks according to OMCS and IMU showed no significant difference and a good rating of agreement according to both ICC and BA, thus the amplitude differences (peak-trough) of velocity showed no significant difference between the methods. However, the amplitudes of $a\underline{Z}$ peaks did show significant differences ($p < 0.05$) and the variance was also greater at ICC 0.46 (95% CI: 0.35 – 0.57), and thus the amplitude differences (peak-trough) also showed significant differences ($p < 0.05$). The Bland-Altman plot of $a\underline{Z}$ amplitudal peaks (**Figure 16**) seems to demonstrate a proportional error that is not apparent in the plot of $a\underline{Z}$ amplitudal troughs (**Figure 18**). A more systematic error is apparent throughout the other plots, particularly if excepting one consistent horse. Given the small number of subjects (n = 4) it is impossible to say for sure whether this is an anomaly, or whether there is a proportional error associated with IMUs. This offers partial, but incomplete support for the acceptance of H_5 (see section **1.8**), in that there was indeed no difference between IMU and OMCS measurements from the sternum in terms of timings of peaks and troughs, or for amplitudes of velocity peaks and troughs, or acceleration amplitude troughs. However, the hypothesis cannot be accepted for acceleration amplitude peaks.

Since the testing was performed for the current study, Brighton *et al*. (2013) have published data on the comparative accuracies of two different IMU systems: one low cost and one validated system. One unit of each system (256Hz) was located at the *sternum* and the *os sacrum* for six horses trotting in a straight line (n = 48) and lunged (n = 25) overground, where an average trial comprised 25 strides, segmented using *v*<u>Z</u> (according to Starke *et al*., 2012). A systematic error between the two systems was found to increase with deviation from symmetry and corrected using a regression-based approach before further analysis. According to measurements based on *v*<u>Z</u>, the symmetry indices demonstrated a sufficient degree of reliability at both *os sacrum* (mean 0.048mm, LoA ± 0.095) and *sternum* (mean 0.045mm, LoA ± 0.088). However, the difference between the systems at *v*<u>Z</u> minima (mean *os sacrum* 3.36mm, LoA ± 6.6, mean *sternum* 2.52mm, LoA ± 5.02) and maxima (mean *os sacrum* 2.20mm, LoA ± 4.3, mean *sternum* 2.14mm, LoA ± 4.18) were concluded too great for accurate measurement lameness or asymmetry using a low cost IMU.

Whilst Brighton *et al*. (2013) found discrepancy between two IMU systems in the amplitude of *v*<u>Z</u> the current study found no such discrepancy between an IMU system and OMCS. However the current study did find significant differences of amplitude at the peak (maxima) *a*<u>Z</u>. This could be due in part to the fact that validation of IMU against OMCS requires derivation or integration of at least one of the systems; in this study the doubled integration of OMCS data may have caused discrepancies in acceleration data.

Furthermore, validating an accelerometer system against another as in the cases of Brighton *et al*. (2013) and Parsons *et al* (2006) may only produce results indicative of varying degrees of inaccuracy. Brighton *et al*. (2013) referred to the Xsens IMU used in their study as the validated system against which the low cost system was compared. However, in one study (Brodie *et al.,* 2008) into the accuracy of 3D orientation of an Xsens unit (with error reported by the vendor as maximum 3°) in simple pendulum motion, a mean error (compared to OMCS) of 8.5° - 11.7° was found, proportionate to pendulum length (maximum orientation error >30°). With an inaccurate orientation it is unlikely any measurements in any plane can be accurate, although the reliability of the error maybe such that values not dependent on accurate amplitudes (such as symmetry indices) may still be useful. Obviously unless investigators are sure of the accuracy of their gold standard (with or without correction) validity studies are of little value.

It is worth noting that Parsons *et al.* (2006) also concluded that studies where amplitude rather than temporal results were required should not engage the MP3 recorder they described due to the compressive effect of the encoding process.

One study published since testing by Pfau *et al.* (2013) investigated the potential of a single IMU at the *os sacrum* to measure hindlimb lameness. Ten horses undergoing lameness investigations for a range of causes and degrees of hindlimb-lameness were equipped with two IMUs (triaxial, 100Hz) at the *os sacrum* and *tuber coxae* before they underwent the trotted gait assessments required by their diagnosticians. Strides (N = 773) were segmented according to Starke *et al*. (2012). Estimated displacement of the *tuber coxae* (based on a fixed or horse-specific model of the pelvis) from the *os sacrum* IMU resulted in accurate symmetry indices (2% bias) and hip-hike difference (5mm bias) when compared to those measured at the *tuber coxae*. These measures rely on differences between halves of a stride and resulted in a smaller bias than absolute values for maximum (30mm) or minimum (29mm) difference in displacement. Pfau *et al.* (2013) demonstrated a method with a good degree of accuracy with a precision of symmetry indices (bias 11%) suitable for assessment of moderately or more severely hindlimb-lame horses.

Amplitudal results from Pfau *et al*. (2013) proved imprecise (in vertical displacement), as found (though in velocity) by Brighton *et al*., (2013) and in the present study (though in acceleration). Pfau *et al*., (2013) compared an estimated IMU *tuber coxae* movement with a true IMU measurement, and Brighton *et al*., (2013) also compared against another IMU; it is possible that the 'gold standard' IMUs themselves contributed to the amplitudal differences (Brodie *et al.,* 2008).

Although supported by the aforementioned studies, the current study was limited to only four horses (12 trials) in the comparison of IMU and OMCS; the prevalence of the error could be more thoroughly investigated with a larger sample size.

The credibility of temporal event accuracy (after correction) presented the current study remains in accordance with other studies (to the author's knowledge).

4.3 Stance from trunk

The first peak of OMCS GM *a*Z̲ after crossing above 0m/s^{-2} provided beginning of stance timings that were not significantly different from hoof *v*X̲, whilst the highest peak of GM *v*Z̲ provided end of stance timings that were not significantly different from hoof *v*X̲. This lead to the acceptance of H_3 (see section **1.8**) that the beginning and end of stance was identifiable by both OMCS hoof markers and GM.

Starke *et al*. (2012) used an Xsens IMU located at the *os sacrum* (100Hz) and compared the signal with biaxial accelerometers (1000Hz) located on the dorsal midline of one hind hoof (MP3 data logger on the cannon) of ten horses (4596 stances) trotted overground on a straight line and a circle at self selected, slow and fast speeds. Of the output data investigated *v*Z̲ zero-crossing was found to coincide most closely with beginning of stance according to hoof accelerometers, with a mean (standard deviation) of -4(14) – 12(7) ms depending on the condition. Minimum *v*Z̲ was found to coincide with end of stance according to the hoof accelerometer with a mean (standard deviation) of -82(17) to -58(8) ms. The greater degree of systematic error at end of stance may be rectifiable by algorithm although this is not suggested in the article. Although 4596 stances were collected by the *os sacrum* measurements, this would be roughly halved by the fact only one hind hoof was equipped with an accelerometer, and thereby offered validation. Further, with only one hoof being measured, investigation into advanced placement was not undertaken; this could have made comparison possible between similar groups of discipline non-specific horses trotting at self selected speeds overground with those on a treadmill from this study. The zero crossing method to describe beginning of stance presented by Starke *et al*. (2012) had also been recommended in OMCS measurements from the *tuber coxae* by Buchner *et al*. (1993) (there using *a*Z rather than *v*Z) and relies on precision of amplitudal results. Whilst valid in an OMCS system, IMU acceleration amplitudes have been found to be inconsistent in the present study (as well as Parsons *et al.*, 2006; more specifically in Xsens Brodie *et al.,* 2008) and thus methods of their employ should be used with caution until such systems are proven.

Olsen *et al*. (2012) investigated various trunk locations (withers, fourth lumbar vertebrae, *os sacrum* and each *tuber coxae*) compared to the cannon bones as sites for Xsens IMUs (200Hz), however, only *v*Z of the *os sacrum* was found to be comparable to the limb mounted IMUs, and then only for beginning of stance (LoA -11 – 17ms). No method employing the other IMUs, trajectories or gait events was recommended in the journal article, although from the supplementary information it seems that IMUs at the *tuber coxae* and *os sacrum* could detect beginning and end of stance of the hindlimbs using *a*Z and *v*Z respectively, although no values are provided. Similarly, it is suggested (no numerical data available) that the withers and *os sacrum* could detect both beginning and end of stance using *v*X and *a*X respectively. This study unfortunately did not assess the use of the *sternum* as a site for IMU measurements. The previously described queries of the orientation accuracy of Xsens IMUs (Brodie *et al.,* 2008) should not inhibit the accuracy of results in so far as no amplitude values are required, however, it may cast some degree of doubt as to whether the axes described are indeed the exact axes measured, and therefore whether they can be discounted as useful for gait event detection. No data were published by Olsen *et al*. (2012) comparing the time stamps of the separate IMUs with the (presumably) less debatable accuracy of the forceplate, so it remains possible that (in accordance with Parsons *et al*., 2006) the data logging of the 9 IMUs created temporal discrepancy between them, which had repercussions on the comparison of limb mounted and trunk mounted IMUs.

Soft tissue artefacts have been found at 'unacceptable levels' (Goff *et al*., 2010) at the site of the *os sacrum* in skin compared to bone fixed markers. No such investigation has been undertaken of the *sternum* (to the author's knowledge). However given the saddle is designed and girthed for the very aim of anatomical stability, it seems possible that it maybe less subjected to the artefacts. Whilst this is of little significance as regards investigation of temporal characteristics, it may become of greater importance when applied to amplitudal or energetic investigations.

Barrey *et al.* (1995) compared two uni-axial accelerometers (50Hz) located at the *sternum* with a video camera filmed from a car moving parallel to the track on which 24 horses were trotted in harness at a range of speeds. Methods to separate swing from stance according to video footage were not described but did not involve high-speed cameras or markers so may be considered as estimates. The graph depicting stance according to $a\underline{Z}$ of the *sternum* does not describe precise event markers, but seems to suggest either the trough, or the peak immediately after the trough as both beginning and end of stance, allowing for no aerial phase, nor describing any advanced limb placement as was found by Drevemo *et al*. (1980) in similar horses at comparable speeds.

Barrey *et al.* (2001) in this further study used the *sternum* as a site for two uniaxial accelerometers (50Hz) from which to gather *a*Z and *a*X data as horses galloped up a dirt track. Temporal gait information and stride characteristics (such as midstance, contact time, suspension phase duration, as well as beginning and end of stance) were inferred by a Matlab 5 from the accelerometer, although the precise methods of this or their validation remain unreferenced. No OMCS, limb based accelerometry or forceplate measurements were described.

Leleu *et al*. (2002) compared a triaxial accelerometer (100Hz) in the same location (*sternum*) connected to an unspecified data logger on the sulky shaft of three French trotters trotting up a sand track at a range of speeds (8.33 – 13.9 m/s) passing a single camera (200Hz) at a distance of 40m, for 6-10 consecutive strides per trial. Comparison of their definition of stance (as the frame before any distal extension of the fetlock, unclear whether fore or hind) with *a*Z led them to describe beginning of stance in this signal as the trough immediately before the main peak which is in contrast with the current study which found the peak itself to coincide with beginning of stance according to hoof markers. Leleu *et al*. (2002) also described differences between left and right diagonal that they attributed to the high-speed camera filming only from the left side and therefore the right was less well visualized. The intrinsic sources of potential error with the definition of stance according to hoof markers used by Leleu *et al*. (2002) have been described in section **4.1**. In the discussion it was stated that *'the* *image analysis…provides other temporal information about brief events, such as diagonal advanced placement' (*Leleu *et al*., 2002). However no mention of it was made in the results so it is not possible to tell whether such a feature was apparent in these horses as was found by Drevemo *et al*. (1980) in other harness trotters at similar speeds (advanced forelimb placement). It is possible that if advanced forelimb placement occurred and stance was defined according to the forelimbs this could have contributed to the differences between their results and those of the current study as regards features of *a*Z̲ coinciding with beginning of stance. Further, whilst hoof slip in relation to fetlock extension has not (to the author's knowledge) been reported, the time length of hoof slip reported by Holden Douilly *et al*. (2013) (of horses trotting on firm wet sand at 7m/s) is similar to the time difference between the trough before the peak and the peak on the *a*Z̲ graph. Thus perhaps differences between definition of stance between the current study and Leleu *et al*. (2002) led to inclusion and exclusion of hoof slip respectively, accounting for the difference in findings of synchronous events of the *a*Z̲ graph. The methods for identifying end of stance according to Leleu *et al*. (2002) employ *a*Z̲ and are therefore not directly comparable to the methods presented in this study (highest peak of GM *v*Z̲). However, it is unclear whether end of stance was defined according to fore or hind limbs and similarly whether the advanced forelimb lift –off found by Drevemo *et al*. (1980) was apparent.

No significant difference was found at beginning or end of stance between hoof marker trajectories *v*X̲, *v*Z̲, and *p*Z̲. Although measurements were reliable, their accuracy could have been more thoroughly investigated using a forceplate or hoof mounted IMUs or accelerometers. However, given the rarity of forceplate embedded treadmills this most likely would have had to form part of a separate overground experiment. Further, the error associated with MP3 logging (Parsons *et al.*, 2006) at the cannon bone as used in other hoof-mounted studies (Witte *et al*., 2006; Starke *et al*., 2012) as well as the potential for tactile stimulation causing deviation from normal gait (Clayton *et al*., 2008; 2010) would have potentially substituted limitations, rather than eliminating them altogether.

4.4 Conclusion

The current study found that IMU data can be unreliable in terms of acceleration amplitude (in accordance with Brighton *et al.,* 2013) and in terms of time drift (in accordance with Parsons *et al*., 2006) suggesting the need for caution when interpreting results from unverified data, or from methods involving amplitudal information such as zero-crossing.

An OMCS marker located on the girth was consistently visible to the cameras used in this set up, particularly compared with hoof markers. A correctly fitted girth is, by design, likely to remain more anatomically stable than a skin attachment. However, this should be validated against bone fixed markers for algorithm development if truly precise energetic inferences are to be made.

Further investigation is also required to ascertain the effectiveness of these methods in identifying stance of individual limbs where horses exhibit advanced limb placement not found in animals studied here, but potentially found in elite horses (dressage or trotters at a range of speeds).

OMCS data and temporal IMU data have been used to validate an effective new method for defining beginning and end of stance using $a\underline{Z}$ and $v\underline{Z}$ respectively from data collected at the *sternum* of non-elite horses trotting at self selected speeds on a treadmill. This site and the methods presented have potential to offer convenient measurement of accurate stride characteristic information in other gaits, as well as overground on a variety of surfaces, subject to further validation.

5 Appendix

5.1 SOP for QTM and equine treadmill testing

SOP TITLE: *Qualisys Track Manager and Equine Treadmill Testing*

Version Number:

	NAME	SIGNATURE	DATE
Author			
Reviewer			
Authoriser			

Effective Date:	
Review Date:	

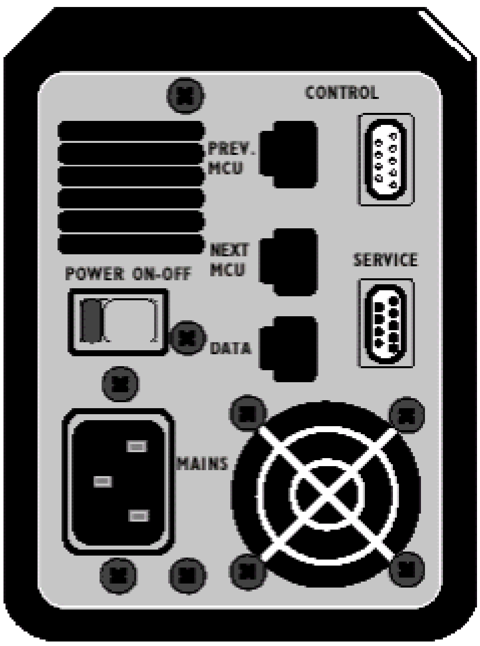
Version	Date	Reason for Change

This Standard Operating Procedure (SOP) is to be followed by researchers when measuring Equine Gait with the Movement Science Group, Oxford Brooks University.

Introduction	Qualisys Track Manager (QTM) 1.9.2xx is a Windows-based data acquisition software with an interface that allows the user to perform 2D and 3D motion capture. During capture, real time 2D, 3D and 6D camera information is displayed allowing instant confirmation of accurate data acquisition. Each camera gathers 2D data from each marker, if the marker is visible by more than one camera, the information is processed and converted into 3D or 6D data by advanced algorithms. The data can then be exported to analysis software (Excel).

Equipment	• A camera system comprising
	  ○ 7 cameras on tripods
	  ○ A serial communication board
	• A 750mm wand calibration kit and L-frame
	• The QTM laptop with installed Software
	• 4 circular adhesive hoof markers (2cm diameter)
	• 1 semi-spherical reflective girth marker

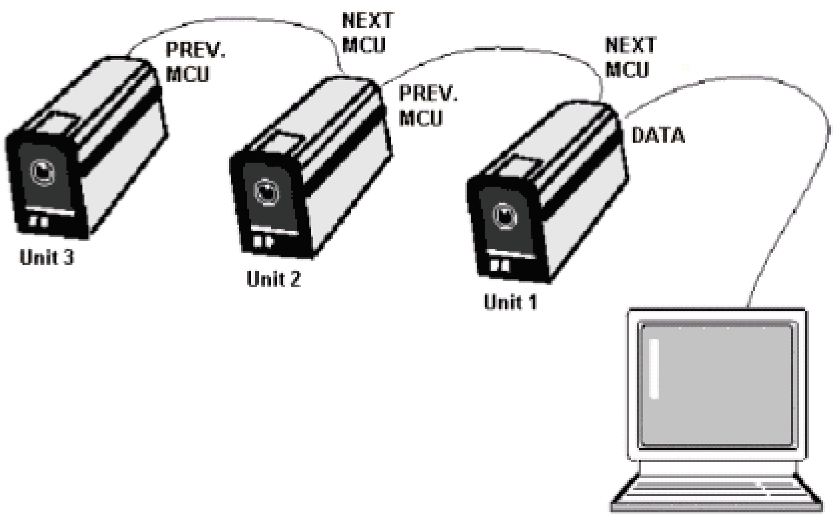
Procedure	<u>**Setting up the system:**</u> 7 Motion Capture Units (MCUs) will be used in a 3D motion capture system, where the units are connected to each other with the **Next MCU** and **Prev. MCU** ports. The entire camera system is then connected to the measurement computer with the **Data** port of the master MCU. Use the cables that are distributed with the system to connect the system.



Rear of camera view

To set up the system, go through the following steps:

1. Connect the data cables (blue) between the MCUs. The IDs of the cameras can be set in any order.
2. Connect the RS 422 cable (yellow) between the **Data** port of the master MCU and the RS 422 port on the serial communication board in the measurement computer. Note: If a regular COM port is used, connect the RS 232 cable (black RJ45 connector) between the **Data** port of the master MCU and the COM port.
3. Set all power switches to off and connect all units to power supplies.
4. Switch on the power supply of the master MCU. All other units will then be automatically switched on.



Arranging the cameras

Once the system has been properly set up, the cameras must be arranged to the current measurement setup. When arranging the cameras, it is best if they are in operating mode. Start the measurement computer and the QTM software. Connect camera system to QTM on the **Connection** page in the **Project options** dialog. Open a new file with a **2D view** window.

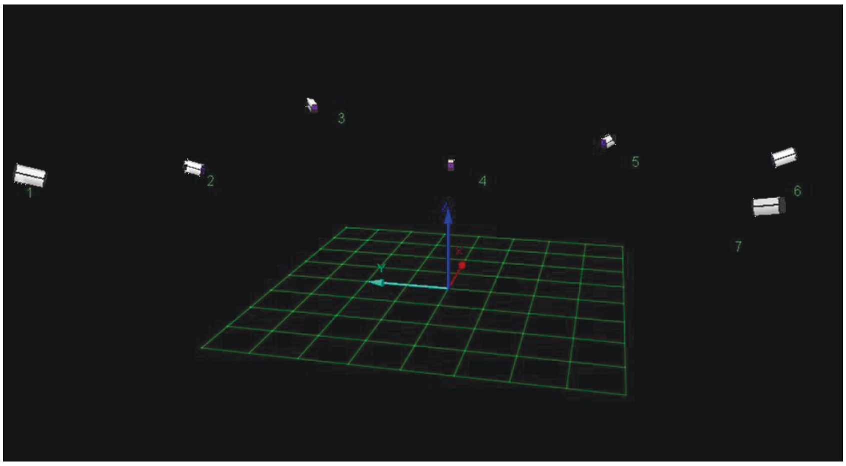
- To reconstruct 3D, data at least two cameras must see each marker during the measurement. Therefore it is best to position the cameras so that as many cameras as possible see each marker during the measurement.
- The angle of incidence between any two cameras should ideally be more than 60 degrees and at least more than 30 degrees. The accuracy of the 3D data calculated from only two cameras placed at less than

30 degrees can degrade below usable levels.

- In order to avoid unwanted reflections, position the cameras so that every camera's view of flashes from other cameras is minimized. E.g. put the cameras above the measurement volume so that the cameras have an angle of about 20 degrees in relation to the floor.
- Obviously the cameras must also be positioned so that they view the volume where the motion of the measurement subject will occur. Mark the volume by putting markers in the corners of the base of the measurement volume. Then make sure that all markers are visible by at least 2 cameras in the 7-camera **2D view** window in preview mode. Preferably, the cameras should not see much more than the measurement volume.

  3 cameras should be placed therefore down each side of the treadmill at a height of about 5'8" and the 7th camera should be placed in front of the treadmill at about 2' in order to see between the horses' front legs.

Note: Remove the markers in the corners before the actual motion capture is started.



Frequency:

In the QTM software on the **Camera System** page, in the **Workspace options** dialog, adjust the frequency to 100Hz.

Focus:

Place the semispherical marker at the furthest possible distance within the measuring volume from the camera and adjust the focus (using the ring closest to the front of the camera under the access door on the top of the camera) to about 6-8 m.

Aperture:

Adjust the aperture (the ring closest to the back of the camera under the access door on the top of the camera) until the **# Markers** display on the front of the camera shows '1' marker and approximately seven to eight bars of the level indicator are filled.

Automatically Connect the System:

1. Switch on the camera system and start QTM
2. Open the **Workspace Options** dialog and go to the **Connection** page.
3. Click **Locate system.**
4. Click **start.**
5. Choose the camera system and click **OK**

Wand Calibration:

The 750mm Wand Calibration method uses a calibration kit that consists of two parts: an L-shaped reference structure and a calibration wand.

Place the L-shaped reference structure so that the desired coordinate system of the motion capture is obtained. It is best if all cameras in the system can see all markers on the reference structure.

A calibration process is started with the **Calibration** dialog, opened by clicking calibrate on the capture menu.

In this dialog, make sure all 7 linearization parameters have been loaded. And adjust **Calibration Quality** to 15 seconds. Click ok and move the calibration wand in a spinning motion inside the measurement volume (up to about 2'3" the full length and width of the treadmill) in all three directions. This is to assure that all axes are properly scaled.

The **Calibration Results** dialog is shown after a calibration is completed. It displays if the calibration passed and the calibration quality results. If it is failed, consult user manual and retry. When passed, **export** the calibration results to a txt file, and remove wand and L-frame.

3d Tracking test:

Perform a 3D tracking test to make sure 3D information can be inferred by the camera setup. Use one markered horse on the treadmill, and a marker in each corner of the measurement volume, and walk and trot the horse briefly completing a single 10-second trial for each condition.

1. Open a new QTM file and perform a capture (capture period = 10 seconds = 1000 frames.
2. Check the number of trajectories in the unidentified trajectories window: Ideally this should match the number of markers (9 = 5 on the horse, and 4 on the corners of the measuring volume), however it is possible that some markers are obscured (by handlers or other) or other markers appear (by varying light

conditions, inappropriate aperture, or by gaps resulting in one marker being identified as separate markers).

3. Check that all 9 placed markers can be seen throughout the measurement – easiest if the measurement is viewed from above in the XY-view.

   Erroneous markers should be accounted for; these can be altered by **camera or aperture alteration, which must be followed by recalibration and a repeat of the 3D tracking test.**

   Extra static markers resultant of sunlight reflection can be deleted from the unidentified markers list at processing, so are less of a concern than obscured markers, or those which are difficult to identify from measurement markers.

   Once satisfied with the results, remove the markers in each corner of the treadmill and begin measurement.

Measurement:

Before starting a measurement you must open a new empty capture file with New on the File menu.

Specify the capture settings in 'start capture' dialog:

- 10 second capture period = 1000 frames

Press start to begin recording.

NB: IF SIMULTANEOUS IMU RECORDING IS REQUIRED, TAP EXTENT SENSOR WHEN CLICKING START ON QTM – SEE PROCEDURE POINT 12: PLACING OF THE EXTENT SENSOR IN EQUINE PHILIPS PI-NODE SOP.

At the end of the 10-second sample, name the measurement according to horse and trial number, so that it can be identified and associated with IMU measurement (if required) and animal data collection sheet.

Data processing:

Due to the number of markers, large measuring volume and testing conditions, **Batch Processing is not recommended.**

Unidentified trajectories can be viewed, combining parts of each marker if a gap appears, and an AIM model can be applied (5 marker horse model)– though must be thoroughly checked second by second, marker by marker, as gaps result in occasional marker swapping. In some measurements it may be easier not to use the AIM model.

Accounted for and irrelevant marker appearances can be deleted from the unidentified trajectory list.

Contrary to the User Manual, it is recommended that **Gap Fill** be only executed once all trajectories are labelled. Click on 'fill gaps' and consider carefully the length of the gap, and the shape of the suggested fill in all three axes, in comparison to the pattern of neighbouring measured strides before accepting the fill.

Export:

	Export (File, Export, To TSV) to 3D tsv export for analysis in excel, in the TSV export setting dialog, tick ‘exclude unidentified trajectories’, and ensure all 1000 frames are included in the selected range. Upon opening in excel, the file header will be composed of the following variables: NO_OF_FRAMES (total number of frames in exported file - 1000) NO_OF_CAMERAS (for the motion capture of this file - 7) NO_OF_MARKERS (identified in the trajectories in QTM - 5) FREQUENCY (Measurement frequency used in the motion capture -100) NO_OF_ANALOG ANALOG_FREQUENCY DESCRIPTION TIME_STAMP DATA_INCLUDED (3D) MARKER_NAMES (according to AIM model) The positional trajectory data (mm) is then stored in columns, each row representing one frame. Each trajectory has one column for each direction (X, Y, Z). The data for the first marker therefore is columns A-C, the second marker D-F and so forth.
Further considerations	**<u>Safety:</u>** The ProReflex camera uses short but quite strong infrared flashes to illuminate the markers. The flash is generated by LEDs on the front of the camera. The ProReflex camera complies with the FDA CFR 1040.10 Class I classification that means that the LED radiation is not considered to be hazardous. However, any light of high intensity might be harmful to your eyes, and as infrared light is invisible to human eyes, you can be exposed without noticing. Therefore, in the interests of safety, do not stare directly at the LEDs at a short distance for a prolonged time period.
Miscellaneous	

5.2 SOP for Equine Phillips Pi-Node

SOP TITLE: *Equine Phillips Pi-Node*

Version Number:

	NAME	SIGNATURE	DATE
Author	Bea Bathe		
Reviewer			
Authoriser			

Effective Date:	
Review Date:	

Version	Date	Reason for Change

This Standard Operating Procedure (SOP) is to be followed by researchers when measuring equine gait with the Movement Science Group, Oxford Brooks University.

Introduction

The Pi-Node employs three different sensor modalities to calculate an estimate for its 3D orientation in space: 3D accelerometers (to measure mainly the direction of gravity), 3D magnetometers (to measure the direction of the Earth magnetic field) and 3D gyroscopes (to measure rotation speed along three orthogonal axes). After reading these sensors the analog values are converted to the digital domain by a 16-bit A/D converter.

The calibrated (corrected for sensor offset variations, sensor gain variations and component orientation variations) sensor outputs are sent to the host PC via a wireless AquisGrain communication link. This link is based on the IEEE 802.15.4 physical link; with the proprietary AquisGrain protocol on top that taking care of node enumeration and time synchronization.

The Pi-Node has some properties that control the sampling:

- **usPerSubSample** – expressed in micro seconds, this defines the sample rate of the Pi-Done, before decimation. For this procedure the value is 10000 (which is equal to 100Hz).
- **subPerSample** – this defines the decimation factor. For this procedure the value is 4 (which yields an effective sample rate of 25Hz when usPerSubSample is 10000).
- **samplePerPacket** – defines how many samples (after decimation) are transmitted in one RF-packet. For this procedure a value of 3 samples per packet (of 25Hz decimated, 100Hz before decimation) is employed.

Further details of Pi-Node use can be found in the Philips sense and simplicity Pi-Node User Manual.

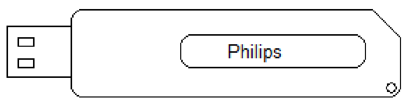
Equipment

2 x Philips Pi-Node sensors
Philips Bluetooth receiver USB stick
Fizzbook laptop PC and installed relevant software
Double-sided tape
Surcingle or girth
Adapted tail guard

Procedure

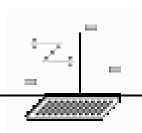
SETUP OF THE BASE SENSOR:

1. Plug the Philips USB stick in the USB-port of the computer:

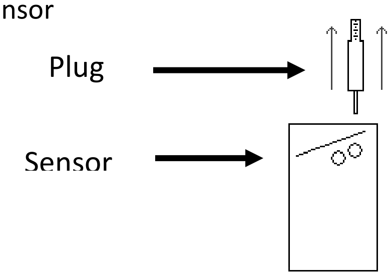


2. Wait for the red LED in the Philips USB stick to flash

3. Start the Philips Pi-Node software by double clicking the desktop icon as showed below:

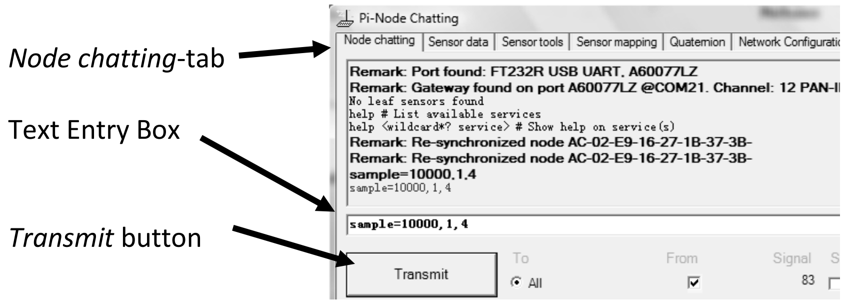


4. Unplug the Philips Pi-Node sensor

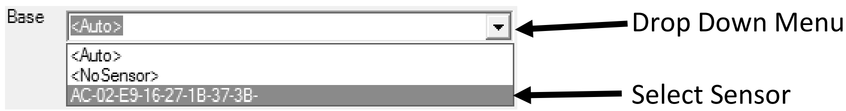


5. Wait for the LED to flash green on the sensor as well as inside the USB stick

6. Go to the *Node chatting*-tab and type *sample=10000,1,4* into the text entry box (white input box) and press *Transmit*:



7. Go to the *Sensor mapping*-tab and assign the sensor to the *Base* in the drop-down menu:



SETUP OF THE EXTENT SENSOR:

8. Follow steps 4) to 6) precisely with the second Pi-node. At step 7) assign the sensor to Extent in the drop down menu.

PLACING THE BASE SENSOR:

9. Align the sensor with the surcingle or girth, as it will be attached to the horse ensuring the following:
    - The X plane is orientated with the craniocaudal plane of the horse – positive being cranial
    - The Z plane is orientated with the dorsoventral plane of the horse – positive being dorsal
    - The Y plane is orientated with the mediolateral plane of the horse – positive being right.

10. Using double-sided tape and the protective cover of the adapted tail guard, attach the sensor securely to the *inside* of an elasticated surcingle (or the *outside* of a saddle girth - in ridden or tack trials), and close the Velcro of the tail guard

away from the horse.

11. Attach the surcingle so that the sensor lies over the *sternum* between the *pectoralis profundi*, and the surcingle encircles the rib cage about one hands width behind the olecranon process of ulna (point of elbow). An elasticated girth or surcingle should be fastened skin tight (such as one flat palm can just pass beneath), with the clip to one side of the barrel over soft tissue. A non-elasticated girth should be fractionally tighter. If any rotation of the strap can be procured, tighten further.

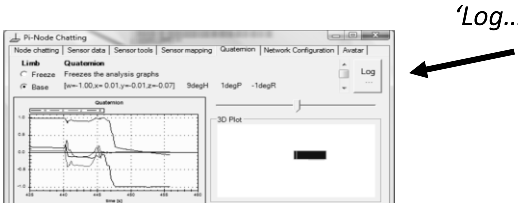
PLACING OF THE EXTENT SENSOR:

12. Place the Extent sensor on a flat cushioned surface close to the Qualisys laptop. Begin sensor recording first (steps 13 – 15), and commence Qualisys measurement as required. Upon beginning Qualisys measurement, firmly tap the Extent sensor, in order to aid synchronisation of the Base sensor with the Qualisys data.

RECORDING:

13. Go to the *Quaternion*-tab (when using the fizz book select the 'freeze' button to disable graphics) and press the '*Log…*' button on the right side, assign a folder and file name and press '*Save'* to start recording

'Log…' button



14. When done recording press the *'Log…'* button ONCE to STOP recording

15. Repeat step 12 & 13 to record another measurement.

Further considerations	A large number of samples per packet increases the effective RF bandwidth (b reducing overhead), but increases latency. Check packaging before interpreting temporal information.
Miscellaneous	The Philips Pi-Node conforms to the following directives: Ratio & Telecommunications Terminal Equipment R&TTE 1999/5/EC Electromagnetic compatibility EMC 2004/108/EC

5.3 SOP for Equine Treadmill Familiarisation

OXFORD BROOKES UNIVERSITY

Movement Science Group

SOP TITLE: *Equine Sato I Treadmill Familiarisation*

Version Number:

	NAME	SIGNATURE	DATE
Author	Bea Bathe		
Reviewer			
Authoriser			

Effective Date:	
Review Date:	

Version	Date	Reason for Change

This Standard Operating Procedure (SOP) is to be followed by researchers when familiarising horses with treadmill exercise with the Movement Science

Group, Oxford Brooks University.

Introduction	The treadmill used was a certified Sato I. Which allows speeds ranging from 0-16m/s and 0-10% (or 6 degree) incline, whilst surrounded by strong bars to ensure the safety of horses and handlers. The treadmill comes with a wall mounted LCD display device that reports speed and slope to the operator. **FAMILIARISATION WITH TREADMILL EXERCISE MUST BE UNDERTAKEN BEFORE ANY TREADMILL TESTING CAN BE UNDERTAKEN** Personnel • **Dr. Kathryn Nankervis** and **Felicity Marshall** are responsible for training any treadmill operators and assisting staff, and are in charge of designating the person or persons who are qualified to operate the treadmill and supervise exercise sessions. • **Dr. Kathryn Nankervis** and **Felicity Marshall** are also in charge of resolving disputes regarding a horse's fitness, soundness, familiarity with the exercise, preferred speeds, length of session, and training methods. Up to three people may be required to assist for each exercise session (as determined by Dr. Kathryn Nankervis and Felicity Marshall)– those performing any experimental procedure may not be included.
Equipment	In addition to the treadmill itself, other equipment that should be included in each exercise session include: • A nylon halter or leather bridle and one or two nylon lead ropes with a bull snap • One or two whips • Grain or praise method • Gloves and hats for all handlers • A lunge line attached to the back of one side barrier and held by the handler on the opposing side to discourage the horse from stepping back off the treadmill • A timer • A cart on which to lay miscellaneous necessary items within reach of the operator • Any necessary floor mats or wall mats for the horse's protection • Portable fans for cooling during exercise
Procedure	Most horses require a minimum of two to three training sessions on the treadmill before an exercise test can be attempted. Furthermore, developing a training protocol and a timeframe for performing an exercise test depends on the following factors: • The horse's previous experience with treadmill exercise. • The horse's initial reaction to walking on the treadmill. • The horse's ability to trot safely on the treadmill. • The horse's willingness and safety to canter on the treadmill.

Preparing for a training session:

The operator is responsible for assembling the appropriate equipment, preparing the treadmill area and establishing that the horse has been certified as fit and sound for attempts at treadmill exercise by the senior clinician responsible for the case.

a. Preparing the treadmill area.
    - Ensure that rubber mats are placed over all cement surfaces around the treadmill to prevent the horse from slipping.
    - Ensure the wall behind the treadmill is appropriately padded in case the horse trips.
    - Clear all other unnecessary movable objects from around the treadmill.
b. Inspect the treadmill.
    - Turn on the treadmill (the switch at the electrical box is moved from 0 to 1, and the key is inserted into the emergency stop button and turned until the light display comes on). Check that the speed control is advancing the treadmill properly and that the LCD display screen is imparting information (the LCD screen is turned on using the remote contained within a protective Ziploc bag).
    - Turn on the fans in front of the treadmill to ensure they are operating.
    - Inspect the belt to ensure it does not have excessive grease that makes it slippery or that the center is not too worn.
    - Ensure the lubricant reservoir contains an adequate volume by inclining the treadmill to 10% and removing the side panel to observe. The reservoir should be marked with a line at the level of the lubricant and the date of inspection using the dry erase pen.
c. Assemble necessary equipment.
    - Nylon halter or leather bridle and one or two nylon lead rope(s) with a bull snap. The bridle may be used for leading a horse on and off the treadmill, but the halter must be used when the treadmill is in motion
    - Whip(s)
    - Grain or praise method
    - Gloves and hats to be worn by all handlers
    - Timer
    - Cart to be placed by the treadmill control panel.
d. Inspect the horse for the following.
    - The operator inspects the horse for temperament, ability to lead and tie, and propensity to pull back in response to head restraint.
    - The operator and the senior medicine clinician or surgery clinician ensure significant lameness/ tendon/suspensory ligament disease that may be exacerbated by exercise is not present.

NOTE: ANY QUESTIONS REGARDING THE HORSE'S SUITABILITY

FOR TREADMILL EXERCISE SHOULD BE DIRECTED TO <u>DR. KATHRYN NANKERVIS</u> OR <u>FELICITY MARSHALL.</u>

<u>First stage session</u>

1. During the first stage exercise session, the following should occur:
   a. The exercise portion of the session, not the session itself, should last no more than 15 minutes and should include the horse learning to walk and stop on the treadmill, while being offered handfuls of grain as a reward.
   b. If the horse is very comfortable, the operator can increase the speed from a walk to a trot.
   c. The incline is not used during the initial session.
   d. The horse should be encouraged to walk with its head over the padded front bar.
2. The first stage session consists of one operator and three assistants:
   a. The operator positions at the controls where they start the timer, operate the treadmill controls, and have a finger positioned above the emergency stop button at all times.
   b. One gloved assistant, the "holder," holds a rope attached to the horse's halter. This person leads the horse onto the treadmill, halts holds the horse's head while the horse is on the treadmill, and reverses the horse off the treadmill. They must always hold the rope and avoid putting their fingers or thumb close to the snap or halter
   c. Two assistants position themselves at the right and left rear flanks of the horse and offer encouragement.

REPEAT 2-3 TIMES.

3. The operator starts the timer.
   a. While the horse is standing off and to the side of the treadmill, the operator turns the treadmill on and off to show the horse and to accustom it to the noise.
   d. The holder walks the horse onto the treadmill, halts, and praises or feeds the horse.
4. Two assistants with a short whip are positioned near each flank of the horse and are responsible for keeping the horse toward the front of the treadmill while the treadmill is in motion. These assistants verbally encourage the horse to walk forward, using whips if necessary.
   Depending on the horse, to provide a sense of security and to keep the horse from drifting too far back, assistants may wrap the lunge rope around the back of the horse and loop each end of the rope over a side bar. The rope should not be tied so that it can be quickly disengaged at any time.

Note: While the treadmill is running (step 5), the holder is positioned either in front or beside the treadmill. If the horse has a tendency to pull back when the head is restrained, the holder should stand beside the treadmill.

5. With the horse and three assistants in place, the operator turns on the treadmill at the walk or lowest speed: 1.8 – 1.9 m/s.

DANGER

The operator determines how much encouragement is necessary and should immediately stop the treadmill if the hind legs of the horse reach a non-moving part at the back of the treadmill.
Meanwhile, holder exerts steady pressure instead of pulling on the rope. The holder must never release the rope. If the holder cannot keep the horse's chest up to the padded front bar, the holder should maintain tension while gradually releasing the rope. If the holder drops the rope, horse will fly backward potentially causing serious injury or death.

6. If the horse is doing well, the operator can increase the speed to 3-4 m/s for one to two trot cycles of no more than 2 minutes each, with a two minute walk cycle between each trot cycle.
   a. Note: The operator notifies personnel when the speed is changing. Trot speeds are relative and should be adjusted to accommodate the horse.
7. If the horse has been trotted, the session ends with a two minute walk cycle at 1.8 – 1.9 m/s.
8. The operator turns off the treadmill and stops the timer.
9. The operator or holder removes the lunge rope from behind the horse (if used)
10. The holder reverses the horse off the treadmill.
11. The operator determines how the horse is cooled down (hose, walk, both) and if the horse is able to participate in the second session. A one-hour rest should occur before the next exercise session begins.

AT THE OPERATOR'S DISCRETION, THIS STAGE MAYBE REPEATED INDEFINITELY (WITH MINIMUM ONE HOUR BREAKS IN BETWEEN) BEFORE MOVING ONTO THE SECOND STAGE, UNTIL THE HORSE IS CALM AND CONFIDENT WITH THE PROTOCOL.

<u>Second stage session:</u>

After a minimum of one-hour break, a second stage 20-minute training session can be performed. Again, no incline is used.
The second stage session consists of one operator and two or three assistants:
If the horse was very comfortable on the treadmill during the first session, one operator and two assistants may be sufficient, however, three people should be available to assist, if necessary:

- One operator is positioned at the controls where they start the timer, operate the treadmill controls, and have a finger above the emergency stop button at all times.
- One gloved assistant leads the horse on to the treadmill, holds the horse's head while the horse is on the treadmill,

and reverses the horse off the treadmill.

- One gloved assistant attaches a rope to the other side of the halter when the horse is on the treadmill to assist straightness.

1. The operator starts the timer.
2. The holder walks the horse on to the treadmill, puts the lunge rope behind (if used), and feeds the horse a few handfuls of grain, while the other assistant gives the walk on command from behind.

One or two assistants with a short whip are responsible for keeping the horse toward the front of the treadmill while the treadmill is in motion. One assistant positions himself/herself by the horse's right rear flank. A second assistant, if necessary, positions himself/herself by the horse's left flank. Assistants verbally encourage the horse to walk forward, using a whip if necessary.

3. The operator turns on and starts the treadmill at the walk or lowest speed: 1.8 – 1.9 m/s.

DANGER

The operator determines how much encouragement is necessary and should immediately stop the treadmill if the hind legs of the horse reach a non-moving part at the back of the treadmill.

Meanwhile, holder exerts steady pressure instead of pulling on the rope. The holder must never release the rope. If the holder cannot keep the horse's chest up to the padded front bar, the holder should maintain tension while gradually releasing the rope. If the holder drops the rope, horse will fly backward potentially causing serious injury or death.

4. The horse is encouraged to walk with its head over the padded front bar for 4 minutes at 1.8 – 1.9 m/s to warm up. After 4 minutes, the operator lets the assistants know the treadmill speed will increase. The following is a guideline for the session.

Gait	Duration (minutes)	Speed (m/s)	Comment
1.Walk	4	1.8-1.9	Warm up
2. Trot	2	3-4.5	
3.Walk	2	1.8-1.9	
4. Trot	2	3-4.5	
5. Canter & 5% incline	2	Gradually increase from trotting speed to 9-9.5 and then adjusting back down to sustain the canter at 7-8m/s or where the horse is comfortable	When breaking from trot into canter, assistants encourage the horse with rhythmic slapping as the speed is increased. Canter no more than 2 minutes before dropping to walk
6.Walk	2	1.8-1.9	
7. Trot	2	3-4.5	Steps 7 and 8 are optional.
8. Canter & 5% incline	2	7-8	Canter no more than 2 minutes before dropping to walk

9.Walk	2	1.8-1.9	Cool down. Mandatory.

THIS STAGE MUST BE REPEATED AT LEAST ONCE AFTER A MINIMUM ONE HOUR BREAK, BEFORE TESTING CAN COMMENCE. HOWEVER, AT THE OPERATOR'S DISCRETION, THIS STAGE MAYBE REPEATED INDEFINITELY (WITH MINIMUM ONE HOUR BREAKS IN BETWEEN) BEFORE TESTING, OR INDEED IF THE HORSE PANICS, RETURNING TO STAGE ONE BEFORE PROGRESSING TO STAGE TWO AGAIN, UNTIL THE HORSE IS CALM AND CONFIDENT WITH THE PROTOCOL.

Further considerations

Safety

Personnel observing or participating in a treadmill session should be aware of the following safety concerns *prior* to the session:

- **Be quiet**. The treadmill operator is responsible for the safety of the animal and safe operation of the treadmill. Throughout a session the operator lets personnel know when the treadmill is being turned off and on, and when the treadmill speed is changing. For the sake of the horse, and all personnel, it is critical that unnecessary noise or distractions are avoided during exercise sessions.
- **Know your position**. The treadmill operator is responsible for the positions of observers and participants before, during, and after an exercise session. *Make sure you know where to stand.* If you are a participant, *make sure you know what to do* before the session begins.
- **Remove or secure loose clothing** or anything that could be at risk of entanglement Personnel should *remove or secure loose clothing (like sleeves sand shoe laces) or other dangling items* that could get caught in the treadmill belt.
- **Prevent interruption of the session**. Place a sign on the outside of the door to inform external personnel that a session is underway and that they SHOULD NOT ENTER unless prior arrangements have been made with the operator

Miscellaneous

Treadmill maintenance

The treadmill is maintained on a routine basis by facilities

Weekly	Facilities	Checks there is sufficient lubrication for the belt as indicated by the gauge under the treadmill. Ensure the lubricant reservoir contains an adequate volume by inclining the treadmill to 10% and removing the side panel to observe. The reservoir should be marked with a line at the level of the lubricant and the date of inspection using the dry erase pen. Ensures the belt is not slippery, posing a

		danger to the horse and to personnel.
After each session	Hartpury Team	Cleans manure from beneath the treadmill.
As needed	LAH Hospital crew	The treadmill belt should be cleaned under the direct supervision of the treadmill operator. Prior to belt cleaning, the drain should be clear of debris and manure should be removed. Cleaning should occur prior to a weekend to allow sufficient time for the belt and the area to dry before sessions the following week. Clean the belt using a detergent that leaves no residue. Residue causes the belt to be slippery, which may cause injury to the horse or the equipment.

5.4 SPSS Outputs

T tests

Spssbea text output.dr

T-Test

Notes

Output Created		14-Jun-2012 15:29:09
Comments		
Input	Active Dataset	DataSet6
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	391
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=dhldown /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.032
	Elapsed Time	00 00:00:00.030

[DataSet6]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? dhl down	1	163	.7444	.03059	.00240
	2	160	.7468	.10473	.00828

Independent Samples Test

	Levene's Test for Equality of Variances

		F	Sig.
? dhl down	Equal variances assumed	2.203	.139
	Equal variances not assumed		

Independent Samples Test

		t-test for Equality of Means			
		t	df	Sig. (2-tailed)	Mean Difference
? dhl down	Equal variances assumed	-.287	321	.774	-.00246
	Equal variances not assumed	-.285	185.473	.776	-.00246

Independent Samples Test

		t-test for Equality of Means		
		Std. Error Difference	95% Confidence Interval of the Difference	
			Lower	Upper
? dhl down	Equal variances assumed	.00855	-.01928	.01437
	Equal variances not assumed	.00862	-.01946	.01455

```
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=dhlup
  /CRITERIA=CI(.95).
```

T-Test

Notes

Output Created		14-Jun-2012 15:30:06
Comments		
Input	Active Dataset	DataSet6
	Filter	<none>
	Weight	<none>
	Split File	<none>

	N of Rows in Working Data File	391
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=dhlup /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.031
	Elapsed Time	00 00:00:00.170

[DataSet6]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? dhl up	1	172	.7461	.03196	.00244
	2	173	.7443	.03275	.00249

Independent Samples Test

		Levene's Test for Equality of Variances	
		F	Sig.
? dhl up	Equal variances assumed	.171	.680
	Equal variances not assumed		

Independent Samples Test

		t-test for Equality of Means			
		t	df	Sig. (2-tailed)	Mean Difference
? dhl up	Equal variances assumed	.524	343	.600	.00183

Independent Samples Test

		t-test for Equality of Means			
		t	df	Sig. (2-tailed)	Mean Difference
? dhl up	Equal variances assumed	.524	343	.600	.00183
	Equal variances not assumed	.524	342.884	.600	.00183

Independent Samples Test

		t-test for Equality of Means		
		Std. Error Difference	95% Confidence Interval of the Difference Lower	95% Confidence Interval of the Difference Upper
? dhl up	Equal variances assumed	.00348	-.00503	.00868
	Equal variances not assumed	.00348	-.00503	.00868

```
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=dhrdown
  /CRITERIA=CI(.95).
```

T-Test

Notes

Output Created		14-Jun-2012 15:31:44
Comments		
Input	Active Dataset	DataSet6
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	391
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.

	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=dhrdown /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.031
	Elapsed Time	00 00:00:00.041

[DataSet6]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? dhr down	1	183	.7457	.02796	.00207
	2	151	.7459	.03317	.00270

Independent Samples Test

		Levene's Test for Equality of Variances	
		F	Sig.
? dhr down	Equal variances assumed	2.492	.115
	Equal variances not assumed		

Independent Samples Test

		t-test for Equality of Means			
		t	df	Sig. (2-tailed)	Mean Difference
? dhr down	Equal variances assumed	-.063	332	.950	-.00021
	Equal variances not assumed	-.062	294.119	.951	-.00021

Independent Samples Test

	t-test for Equality of Means

		Std. Error Difference	95% Confidence Interval of the Difference	
			Lower	Upper
? dhr down	Equal variances assumed	.00335	-.00679	.00637
	Equal variances not assumed	.00340	-.00690	.00648

```
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=dhrup
  /CRITERIA=CI(.95).
```

T-Test

Notes

Output Created		14-Jun-2012 15:32:13
Comments		
Input	Active Dataset	DataSet6
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	391
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=dhrup /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.016
	Elapsed Time	00 00:00:00.019

[DataSet6]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? dhr up	1	182	.745	.0328	.0024
	2	173	.742	.0330	.0025

Independent Samples Test

		Levene's Test for Equality of Variances	
		F	Sig.
? dhr up	Equal variances assumed	.049	.825
	Equal variances not assumed		

Independent Samples Test

		t-test for Equality of Means			
		t	df	Sig. (2-tailed)	Mean Difference
? dhr up	Equal variances assumed	.736	353	.462	.0026
	Equal variances not assumed	.736	351.769	.462	.0026

Independent Samples Test

		t-test for Equality of Means		
		Std. Error Difference	95% Confidence Interval of the Difference	
			Lower	Upper
? dhr up	Equal variances assumed	.0035	-.0043	.0094
	Equal variances not assumed	.0035	-.0043	.0094

```
GET DATA
  /TYPE=XLS
  /FILE='C:\Users\HD\Desktop\diag coupling + GM changes.xls'
  /SHEET=name 'Sheet2'
  /CELLRANGE=full
  /READNAMES=on
  /ASSUMEDSTRWIDTH=32767.
```

```
EXECUTE.
DATASET NAME DataSet7 WINDOW=FRONT.
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=FLRHfromgm
  /CRITERIA=CI(.95).
```

down

T-Test

Notes

Output Created		14-Jun-2012 15:33:51
Comments		
Input	Active Dataset	DataSet7
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	388
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=FLRHfromgm /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.046
	Elapsed Time	00 00:00:00.070

```
[DataSet7]
```

Group Statistics

V2	N	Mean	Std. Deviation	Std. Error Mean

? FL RH from gm	1	189	.7455	.03902	.00284
	2	183	.7459	.02995	.00221

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
? FL RH from gm	Equal variances assumed	13.394	.000	-.110	370
	Equal variances not assumed			-.111	351.811

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
? FL RH from gm	Equal variances assumed	.912	-.00040	.00361
	Equal variances not assumed	.912	-.00040	.00360

Independent Samples Test

		t-test for Equality of Means	
		95% Confidence Interval of the Difference	
		Lower	Upper
? FL RH from gm	Equal variances assumed	-.00751	.00671
	Equal variances not assumed	-.00748	.00668

```
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=FRLHfromgm
  /CRITERIA=CI(.95).
```

down
up

T-Test

Notes

Output Created		14-Jun-2012 15:34:43
Comments		
Input	Active Dataset	DataSet7
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	388
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=FRLHfromgm /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.031
	Elapsed Time	00 00:00:00.059

[DataSet7]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? FR LH from gm	1	184	.7438	.03890	.00287
	2	172	.7463	.02855	.00218

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
? FR LH from gm	Equal variances assumed	21.387	.000	-.680	354
	Equal variances not assumed			-.687	335.475

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
? FR LH from gm	Equal variances assumed	.497	-.00247	.00364
	Equal variances not assumed	.492	-.00247	.00360

Independent Samples Test

		t-test for Equality of Means	
		95% Confidence Interval of the Difference	
		Lower	Upper
? FR LH from gm	Equal variances assumed	-.00963	.00468
	Equal variances not assumed	-.00956	.00461

```
GET DATA
  /TYPE=XLS
  /FILE='C:\Users\HD\Desktop\diag coupling + GM changes.xls'
  /SHEET=name 'Sheet3'
  /CELLRANGE=full
  /READNAMES=on
  /ASSUMEDSTRWIDTH=32767.
EXECUTE.
DATASET NAME DataSet8 WINDOW=FRONT.
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=LFRHfromgm
  /CRITERIA=CI(.95).
```

up

T-Test

Notes

Output Created		14-Jun-2012 15:36:13
Comments		
Input	Active Dataset	DataSet8
	Filter	<none>
	Weight	<none>

	Split File	<none>
	N of Rows in Working Data File	378
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.
	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=LFRHfromgm /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.031
	Elapsed Time	00 00:00:00.069

[DataSet8]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? LF RH from gm	1	187	.7444	.03286	.00240
	2	185	.7437	.03235	.00238

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
? LF RH from gm	Equal variances assumed	.221	.638	.210	370
	Equal variances not assumed			.210	369.991

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
? LF RH from gm	Equal variances assumed	.834	.00071	.00338

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
? LF RH from gm	Equal variances assumed	.834	.00071	.00338
	Equal variances not assumed	.834	.00071	.00338

Independent Samples Test

		t-test for Equality of Means	
		95% Confidence Interval of the Difference	
		Lower	Upper
? LF RH from gm	Equal variances assumed	-.00594	.00736
	Equal variances not assumed	-.00594	.00736

```
T-TEST GROUPS=V2(1 2)
  /MISSING=ANALYSIS
  /VARIABLES=RFLHfromgm
  /CRITERIA=CI(.95).
```

T-Test

Notes

Output Created		14-Jun-2012 15:36:45
Comments		
Input	Active Dataset	DataSet8
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	378
Missing Value Handling	Definition of Missing	User defined missing values are treated as missing.

	Cases Used	Statistics for each analysis are based on the cases with no missing or out-of-range data for any variable in the analysis.
Syntax		T-TEST GROUPS=V2(1 2) /MISSING=ANALYSIS /VARIABLES=RFLHfromgm /CRITERIA=CI(.95).
Resources	Processor Time	00 00:00:00.015
	Elapsed Time	00 00:00:00.141

[DataSet8]

Group Statistics

	V2	N	Mean	Std. Deviation	Std. Error Mean
? RF LH from gm	1	186	.7431	.03335	.00245
	2	186	.7424	.03283	.00241

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
? RF LH from gm	Equal variances assumed	.415	.520	.204	370
	Equal variances not assumed			.204	369.908

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
? RF LH from gm	Equal variances assumed	.839	.00070	.00343
	Equal variances not assumed	.839	.00070	.00343

Independent Samples Test

	t-test for Equality of Means

		95% Confidence Interval of the Difference	
		Lower	Upper
? RF LH from gm	Equal variances assumed	-.00605	.00745
	Equal variances not assumed	-.00605	.00745

ICCs

SPSS ICC text output.doc

```
DATASET ACTIVATE DataSet1.
RELIABILITY
  /VARIABLES=dhrup dflup
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:08:15
Comments		
Input	Data	C:\Users\HD\Desktop\spssbeadiagnol1.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	196
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=dhrup dflup /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.000
	Elapsed Time	00 00:00:00.090

```
[DataSet1] C:\Users\HD\Desktop\spssbeadiagnol1.sav
```

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	167	85.2
	Excluded[a]	29	14.8
	Total	196	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.857	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	Value	df1
Single Measures	.750[b]	.675	.809	6.981	166
Average Measures	.857[c]	.806	.895	6.981	166

Intraclass Correlation Coefficient

	F Test with True Value 0	
	df2	Sig
Single Measures	166	.000
Average Measures	166	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type A intraclass correlation coefficients using an absolute agreement definition.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=dfldown dhrdown
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:24:21
Comments		
Input	Data	C:\Users\HD\Desktop\spssbeadiagnol 1.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	196
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.

Syntax		RELIABILITY /VARIABLES=dfldown dhrdown /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.032
	Elapsed Time	00 00:00:00.049

[DataSet1] C:\Users\HD\Desktop\spssbeadiagnol1.sav

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	151	77.0
	Excluded[a]	45	23.0
	Total	196	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.892	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	Value	df1

Single Measures	.806[b]	.742	.856	9.260	150
Average Measures	.893[c]	.852	.922	9.260	150

Intraclass Correlation Coefficient

	F Test with True Value 0	
	df2	Sig
Single Measures	150	.000
Average Measures	150	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type A intraclass correlation coefficients using an absolute agreement definition.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=dhlup dfrup
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:25:41
Comments		
Input	Data	C:\Users\HD\Desktop\spssbeadiagnol 1.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	196
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.

	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=dhlup dfrup /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.016
	Elapsed Time	00 00:00:00.031

```
[DataSet1] C:\Users\HD\Desktop\spssbeadiagnol1.sav
```

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	158	80.6
	Excluded[a]	38	19.4
	Total	196	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.846	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	Value	df1
Single Measures	.735[b]	.653	.799	6.498	157
Average Measures	.847[c]	.790	.888	6.498	157

Intraclass Correlation Coefficient

	F Test with True Value 0	
	df2	Sig
Single Measures	157	.000
Average Measures	157	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type A intraclass correlation coefficients using an absolute agreement definition.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=dhldown dfrdown
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:31:15
Comments		
Input	Data	C:\Users\HD\Desktop\spssbeadiagnol 1.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	196
	Matrix Input	

Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=dhldown dfrdown /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.031
	Elapsed Time	00 00:00:00.031

```
[DataSet1] C:\Users\HD\Desktop\spssbeadiagnol1.sav
```

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	150	76.5
	Excluded[a]	46	23.5
	Total	196	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.961	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	Value	df1
Single Measures	.925[b]	.898	.945	25.569	149
Average Measures	.961[c]	.946	.972	25.569	149

Intraclass Correlation Coefficient

	F Test with True Value 0	
	df2	Sig
Single Measures	149	.000
Average Measures	149	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type A intraclass correlation coefficients using an absolute agreement definition.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
SAVE OUTFILE='C:\Users\HD\Desktop\spssbeadiagnoll.sav'
 /COMPRESSED.
DATASET ACTIVATE DataSet3.
RELIABILITY
  /VARIABLES=dfrdown FRLHfromgm
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:34:21
Comments		
Input	Active Dataset	DataSet3
	Filter	<none>
	Weight	<none>
	Split File	<none>

	N of Rows in Working Data File	194
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=dfrdown FRLHfromgm /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.016
	Elapsed Time	00 00:00:00.020

[DataSet3]

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	171	88.1
	Excluded[a]	23	11.9
	Total	194	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.740	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	Value	df1
Single Measures	.589[b]	.482	.679	3.850	170
Average Measures	.741[c]	.650	.809	3.850	170

Intraclass Correlation Coefficient

	F Test with True Value 0	
	df2	Sig
Single Measures	170	.000
Average Measures	170	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type A intraclass correlation coefficients using an absolute agreement definition.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=dfldown FLRHfromgm
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:36:47
Comments		
Input	Active Dataset	DataSet3
	Filter	<none>
	Weight	<none>

	Split File	<none>
	N of Rows in Working Data File	194
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=dfldown FLRHfromgm /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(ABSOLUTE) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.032
	Elapsed Time	00 00:00:00.030

[DataSet3]

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	182	93.8
	Excluded[a]	12	6.2
	Total	194	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.770	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.628[b]	.531	.708	4.356	181	181	.000
Average Measures	.771[c]	.693	.829	4.356	181	181	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type A intraclass correlation coefficients using an absolute agreement definition.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
GET DATA
  /TYPE=XLS
  /FILE='F:\diag coupling + GM changes.xls'
  /SHEET=name 'gm foot up'
  /CELLRANGE=full
  /READNAMES=on
  /ASSUMEDSTRWIDTH=32767.

Warning.  Command name: GET DATA
(2101) The column contained no recognized type; defaulting to
"Numeric[8,2]"
* Column 7

Warning.  Command name: GET DATA
(2101) The column contained no recognized type; defaulting to
"Numeric[8,2]"
* Column 9

Warning.  Command name: GET DATA
(2101) The column contained no recognized type; defaulting to
"Numeric[8,2]"
* Column 10
EXECUTE.
DATASET NAME DataSet10 WINDOW=FRONT.
```

```
RELIABILITY
  /VARIABLES=LFRHfromgm dflup
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:39:06
Comments		
Input	Active Dataset	DataSet10
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	189
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=LFRHfromgm dflup /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.016
	Elapsed Time	00 00:00:00.020

[DataSet10]

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	185	97.9
	Excluded[a]	4	2.1
	Total	189	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.793	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.657[b]	.567	.732	4.836	184	184	.000
Average Measures	.793[c]	.724	.845	4.836	184	184	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=dfrup RFLHfromgm
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Reliability

Notes

Output Created		14-Jun-2012 16:40:12
Comments		
Input	Active Dataset	DataSet10
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	189
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=dfrup RFLHfromgm /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00 00:00:00.015
	Elapsed Time	00 00:00:00.009

```
[DataSet10]
```

Scale: ALL VARIABLES

Case Processing Summary

		N	%
Cases	Valid	186	98.4
	Excluded[a]	3	1.6
	Total	189	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.851	2

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0	
		Lower Bound	Upper Bound	Value	df1
Single Measures	.741[b]	.668	.799	6.716	185
Average Measures	.851[c]	.801	.888	6.716	185

Intraclass Correlation Coefficient

	F Test with True Value 0	
	df2	Sig
Single Measures	185	.000
Average Measures	185	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.

b. The estimator is the same, whether the interaction effect is present or not.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=VEL_IMU_PEAK_AMP VEL_QTM_PEAK_AMP
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /SUMMARY=CORR
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:40:28
Comments		
Input	Data	/Users/user2/Documents/velocity imu and qtm.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=vel_IMU_peak_amp vel_QTM_peak_amp /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /SUMMARY=CORR /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.941	.946	2

Summary Item Statistics

	Mean	Minimum	Maximum	Range	Maximum / Minimum	Variance	N of Items
Inter-Item Correlations	.897	.897	.897	.000	1.000	.000	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.889[a]	.856	.914	16.990	203	203	.000
Average Measures	.941[c]	.922	.955	16.990	203	203	.000

```
RELIABILITY
  /VARIABLES=VEL_IMU_PEAK_T VEL_QTM_PEAK_T
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:42:55
Comments		
Input	Data	/Users/user2/Documents/velocity imu and qtm.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=vel_IMU_peak_t vel_QTM_peak_t /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
1.000	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	1.000[a]	1.000	1.000	86943.354	203	203	.000
Average Measures	1.000[c]	1.000	1.000	86943.354	203	203	.000

```
RELIABILITY
  /VARIABLES=VEL_IMU_TR_AMP VEL_QTM_TR_AMP
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:44:17
Comments		
Input	Data	/Users/user2/Documents/velocity imu and qtm.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=vel_IMU_tr_amp vel_QTM_tr_amp /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
.930	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.870[a]	.832	.900	14.379	203	203	.000
Average Measures	.930[c]	.908	.947	14.379	203	203	.000

```
RELIABILITY
  /VARIABLES=VEL_IMU_TR_T VEL_QTM_TR_T
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:45:04
Comments		
Input	Data	/Users/user2/Documents/velocity imu and qtm.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=vel_IMU_tr_t vel_QTM_tr_t /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
1.000	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	1.000[a]	1.000	1.000	65457.723	203	203	.000
Average Measures	1.000[c]	1.000	1.000	65457.723	203	203	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.
a. The estimator is the same, whether the interaction effect is present or not.
b. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.
c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

```
RELIABILITY
  /VARIABLES=VEL_IMU_DIFF VEL_QTM_DIFF
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:45:24
Comments		
Input	Data	/Users/user2/Documents/velocity imu and qtm.sav
	Active Dataset	DataSet1
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=vel_IMU_diff vel_QTM_diff /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
.940	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.887[a]	.854	.913	16.742	203	203	.000
Average Measures	.940[c]	.921	.955	16.742	203	203	.000

```
DATASET ACTIVATE DataSet0.
RELIABILITY
  /VARIABLES=ACC_IMU_PEAK_AMP ACC_QTM_PEAK_AMP
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:46:03
Comments		
Input	Data	/Users/user2/Documents/acceleration imu and qtm.sav
	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=acc_IMU_peak_amp acc_QTM_peak_amp /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
.634	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.464[a]	.349	.565	2.733	203	203	.000
Average Measures	.634[c]	.518	.722	2.733	203	203	.000

```
RELIABILITY
  /VARIABLES=ACC_IMU_PEAK_T ACC_QTM_PEAK_T
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:46:44
Comments		
Input	Data	/Users/user2/Documents/acceleration imu and qtm.sav
	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=acc_IMU_peak_t acc_QTM_peak_t /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
1.000	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	1.000[a]	1.000	1.000	23365.257	203	203	.000
Average Measures	1.000[c]	1.000	1.000	23365.257	203	203	.000

```
RELIABILITY
  /VARIABLES=ACC_IMU_TR_AMP ACC_QTM_TR_AMP
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:47:17
Comments		
Input	Data	/Users/user2/Documents/acceleration imu and qtm.sav
	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=acc_IMU_tr_amp acc_QTM_tr_amp /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
.898	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.815[a]	.763	.856	9.792	203	203	.000
Average Measures	.898[c]	.865	.922	9.792	203	203	.000

```
RELIABILITY
  /VARIABLES=ACC_IMU_TR_T ACC_QTM_TR_T
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:48:33
Comments		
Input	Data	/Users/user2/Documents/acceleration imu and qtm.sav
	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=acc_IMU_tr_t acc_QTM_tr_t /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
1.000	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	1.000[a]	1.000	1.000	72112.001	203	203	.000
Average Measures	1.000[c]	1.000	1.000	72112.001	203	203	.000

```
RELIABILITY
  /VARIABLES=ACC_IMU_DIFF ACC_QTM_DIFF
  /SCALE('ALL VARIABLES') ALL
  /MODEL=ALPHA
  /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
```

Notes

Output Created		12-AUG-2013 15:49:18
Comments		
Input	Data	/Users/user2/Documents/acceleration imu and qtm.sav
	Active Dataset	DataSet0
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	204
	Matrix Input	
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the procedure.
Syntax		RELIABILITY /VARIABLES=acc_IMU_diff acc_QTM_diff /SCALE('ALL VARIABLES') ALL /MODEL=ALPHA /ICC=MODEL(MIXED) TYPE(CONSISTENCY) CIN=95 TESTVAL=0.
Resources	Processor Time	00:00:00.01
	Elapsed Time	00:00:00.00

Case Processing Summary

		N	%
Cases	Valid	204	100.0
	Excluded[a]	0	.0
	Total	204	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
.794	2

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.658[a]	.572	.729	4.844	203	203	.000
Average Measures	.794[c]	.728	.843	4.844	203	203	.000

6 References

Adams, S. B. (2012). “Overview of Lameness in Horses: Lameness In Horses” The Merck Veterinary Manual Online *retrieved from* http://www.merckmanuals.com/vet/musculoskeletal_system/lameness_in_horses/overview_of_lameness_in_horses.html?qt=definition%20lameness&alt=sh

Argue, C. K. and H. M. Clayton (1993). "A Preliminary Study of Transitions between the Walk and Trot in Dressage Horses." Cells Tissues Organs **146**(2-3): 179-182.

Arkell, M., Archer, R. M., Guitian, F. J., May, S. A. (2006). "Evidence of bias affecting the interpretation of the results of local anaesthetic nerve blocks when assessing lameness in horses." Veterinary Records **159**(11): 346-349.

Barrey, E., Galloux, P., Valette, J. P., Auvinet, B., Wolter, R. (1993). "Stride Characteristics of Overground versus Treadmill Locomotion in the Saddle Horse." Cells Tissues Organs **146**(2-3): 90-94.

Barrey, E., Hermelin, M., Vaudelin, J. L., Poirel, D., Valette, J. P. (1994). "Utilisation of an accelerometric device in equine gait analysis." Equine Veterinary Journal **26, Supplement 17**: 7-12.

Barrey, E., Auvinet, B., Courouce, A. (1995). "Gait evaluation of race trotters using an accelerometric device." Equine Veterinary Journal **18**: 156-160.

Barrey, E. (1999). "Methods, applications and limitations of gait analysis in horses." The Veterinary Journal **157**(1): 7-22.

Barrey, E., Evans, S. E., Evans, D. L., Curtis, R. A., Quinton, R., Rose, R. J. (2001). "Locomotion evaluation for racing in Thoroughbreds." Equine Veterinary Journal Supplement (33): 99-103.

Boye, J. K., Thomsen, M. H., Pfau, T., Olsen, E. (2014). "Accuracy and precision of gait events derived from motion capture in horses during walk and trot." Journal of Biomechanics **47**(5): 1220-1224.

Bridges, J., (1751). "No foot, No horse: an essay on the anatomy of the foot of that noble and useful animal, a horse." J Brindley, London.

Brighton, C., Olsen, E., Pfau, T. (2013). "Is a standalone inertial measurement unit accurate and precise enough for quantification of movement symmetry in the horse?" Computer Methods in Biomechanics and Biomedical Engineering. *Accessed online at*
DOI: 10.1080/10255842.2013.819857

Brodie, M. A., Walmsley, A., Page, W. (2008). "The static accuracy and calibration of inertial measurement units for 3D orientation." Computer Methods in Biomechanics and Biomedical Engineering **11**(6): 641-648.

Buchner, H. H. F., Kastner, J., Girtler, D., Knezevic, P. F. (1993). "Quantification of hindlimb lameness in the horse." Acta Anatomica **146**(2-3): 196-199.

Buchner, H. H. F., Savelberg, H. H. C. M., Schamhardt, H. C., Merkens, H. W., Barneveld, A. (1994). *a* "Kinematics of treadmill versus overground locomotion in horses." Veterinary Quarterly **16**(sup2): 87-90.

Buchner, H. H. F., Savelberg, H. H. C. M., Schamhardt, H. C., Merkens, H. W., Barneveld, A. (1994). *b* "Habituation of horses to treadmill locomotion." Equine Veterinary Journal **26**(S17): 13-15.

Buchner, H. H. F., Savelberg, H. H. C. M., Schamhardt, H. C., Barneveld, A. (1995). "Bilateral lameness in horses a kinematic study." Veterinary Quarterly **17**(3): 103-105.

Buchner, H. H. F., Savelberg, H. H. C. M., Schamhardt, H. C., Barneveld, A (1997). "Inertial properties of dutch Warmblood horses." Journal of Biomechanics **30** (6): 653-658.

Chateau, H., Robin, D., Falala, S., Pourcelot, P., Valette, J. P., Ravary, B., Denoix, J. M.

Crevier-Denoix, N. (2009). "Effects of a synthetic all-weather waxed track versus a crushed sand track on 3D acceleration of the front hoof in three horses trotting at high speed." Equine Veterinary Journal **41**(3): 247-251.

Chateau, H., Holden, L., Robin, D., Falala, S., Pourcelot, P., Estoup, P., Denoix, JM., Crevier-Denoix, N (2010). "Biomechanical analysis of hoof landing and stride parameters in harness trotter horses running on different tracks of a sand beach (from wet to dry) and on an asphalt road." Equine Veterinary Journal **42 Supplement 38**: 488-495.

Clayton, H. M. (1997). "Effect of added weight on landing kinematics in jumping horses." Equine Veterinary Journal **29**(S23): 50-53.

Clayton, H. M., and Schamhardt, H. C., (2001) "Meaurement Techniques for Gait Analysis" Chapter 3: 56-57, in *Equine Locomotion (2001), Back, W., Clayton, H. M.,* W. B. Saunders, London

Clayton, H. M., White, A. D., Kaiser, L. J., Nauwelaerts, S., Lavagnino, M., Stubbs, N. C. (2008). "Short-term habituation of equine limb kinematics to tactile stimulation of the coronet." Veterinary and Comparative Orthopaedics and Traumatology **21**(3): 211-214.

Clayton, H. M., White, A. D., Kaiser, L. J., Nauwelaerts, S., Lavagnino, M., Stubbs, N. C. (2010). "Hindlimb response to tactile stimulation of the pastern and coronet." Equine Veterinary Journal **42**(3): 227-233.

Degueurce, C., Pourcelot, P., Audigié, F., Denoix, J. M., Geiger, D. (1997). "Variability of the limb joint patterns of sound horses at trot." Equine Veterinary Journal **29**(S23): 89-92.

Drevemo, S., Dalin, G., Fredricson, I., and Hjerten, G. (1980) "Equine locomotion 3: the reproducibility of gait in Standardbred trotters." Equine Veterinary Journal **12**:71-73

Dyson, P. K., Jackson, B. F., Pfeiffer, D. U., Price, J. S. (2008). "Days lost from training by two- and three-year-old Thoroughbred horses: a survey of seven UK training yards." Equine Veterinary Journal **40**(7): 650-657.

Esser, P., Dawes, H., Collett, J., Howells, K., (2009). "IMU: inertial sensing of vertical CoM movement." Journal of Biomechanics **42**(10): 1578-1581.

Ferrari, M., Pfau, T., Wilson, A. M., Weller, R. (2009). "The effect of training on stride parameters in a cohort of National Hunt racing Thoroughbreds: A preliminary study." Equine Veterinary Journal **41**(5): 493-497.

Fuller, C. J., Bladon, B. M., Driver, A. J., Barr, A. R. S. (2006). "The intra- and inter-assessor reliability of measurement of functional outcome by lameness scoring in horses." The Veterinary Journal **171**(2): 281-286.

Goff, L., Van Weeren, P.R. Jeffcott, L., Condie, P., McGowan, C (2010).

"Quantification of equine sacral and iliac motion during gait: a comparison between motion capture with skin-mounted and bone-fixated sensors." Equine Veterinary Journal **42, Supplement 38**: 468-474.

Gomez Álvarez, C. B., Rhodin, M., Byström, A., Back, W., Weeren, P. R. (2009). "Back kinematics of healthy trotting horses during treadmill versus overground locomotion." Equine Veterinary Journal **41**(3): 297-300.

Gustås, P., Johnston, C., Roepstorff, L., Drevemo, S. (2001). "In vivo transmission of impact shock waves in the distal forelimb of the horse." Equine Veterinary Journal **33**(S33): 11-15.

Gustås, P., Johnston, C., Roepstorff, L., Drevemo, S., Lanshammar, H. (2004). "Relationships between fore- and hindlimb ground reaction force and hoof deceleration patterns in trotting horses." Equine Veterinary Journal **36**(8): 737-742.

Gustås, P., Johnston, C. Drevemo, S. (2006). "Ground reaction force and hoof deceleration patterns on two different surfaces at the trot." Equine and Comparative Exercise Physiology **3**(04): 209-216.

Hobbs, S., et al. (2011). "The difference in kinematics of horses walking, trotting and cantering on a flat and banked 10 m circle." Equine Veterinary Journal **43**(6): 686-694.

Holden-Douilly, L., Pourcelot, P., Desquilbet, L., Falala, S., Crevier-Denoix, N., Chateau, H., (2013) "Equine hoof slip distance during trot at training speed: Comparison between kinematic and accelerometric measurement techniques." The Veterinary Journal **197**: 198-204.

Keegan, K. G. (2007). "Evidence-Based Lameness Detection and Quantification." Veterinary Clinics of North America: Equine Practice **23**(2): 403-423.

Holmström, M., Magnusson, L. E., Philipsson, J. (1990) "Variation in conformation of Swedish Wamblood horses and conformational characeristics of elite sport horses". Equine Veterinary Journal. **22**:186-193

Keegan, K. G., Dent, E. V., Wilson, D. A., Janicek, J., Kramer, J., Lacarrubba, A., Walsh, D. M., Cassells, M. W., Esther, T. M., Schiltz, P., Frees, K. E., Wilhite, C. L., Clark, J. M., Pollitt, C. C., Shaw, R., Norris, T. (2009). "Repeatability of subjective evaluation of lameness in horses." Equine Veterinary Journal **42**(2): 92-97.

Keegan, K. G., Wilson, D. A., Kramer, J., Reed, S. K., Yonezawa, Y., Maki, H., Pai, P. F.,
Lopes, M AF (2013). "Comparison of a body-mounted inertial sensor system–based method with subjective evaluation for detection of lameness in horses." American Journal of Veterinary Research **74**(1): 17-24.

Leleu, C., Gloria, E., Renault, G., Barrey, E. (2002). "Analysis of trotter gait on the track by accelerometry and image analysis." Equine Veterinary Journal: Equine exercise physiology **6, Supplement 34**: 344-348.

Leleu, C., Cotrel, C., Barrey, E. (2005). "Relationships between biomechanical variables and race performance in French Standardbred trotters." Livestock Production Science **92**(1): 39-46.

Luhmann, L. M., Wickler, S. J., Hoyt, D. F., Kobluk, C. N., Cogger, E. A. (2000). "Evaluation of shock attenuation in the forelimb of horses wearing boots and wraps." Journal of Equine Veterinary Science **20**(8): 503-510.

McCracken, M. J., Kramer, J., Keegan, K. G., Lopes, M., Wilson, D. A., Reed, S. K. LaCarrubba, A., Rasch, M. (2012). "Comparison of an inertial sensor system of lameness quantification with subjective lameness evaluation." Equine Veterinary Journal **44**(6): 652-656.

McGreevy, P. D., Thomson, P. C. (2006). "Differences in motor laterality between breeds of performance horse." Applied Animal Behaviour Science **99**(1–2): 183-190.

Morales, J. L., Manchado, M., Vivo, J., Galisteo, A. M., Aguera, E., Miro, F. (1998). "Angular kinematic patterns of limbs in elite and riding horses at trot." Equine Veterinary Journal **30**(6): 528-533.

Murray, R. C., Walters, J. M., Snart, H., Dyson, S. J., Parkin, T. D. H. (2010). "Identification of risk factors for lameness in dressage horses." The Veterinary Journal **184**(1): 27-36.

Nauwelaerts, S., Kaiser, L., Malinowski, R., Clayton, HM (2009). "Effects of trunk deformation on trunk center of mass mechanical energy estimates in the moving horse, Equus caballus." Journal of Biomechanics **42**(3): 308-311.

Olsen, E., Andersen, P. H., Pfau, T. (2012). "Accuracy and Precision of Equine Gait Event Detection during Walking with Limb and Trunk Mounted Inertial Sensors." Sensors **12**(6): 8145-8156.

Oosterlinck, M., Pille, F., Huppes, T., Gasthuys, F., Back, W. (2010). "Comparison of pressure plate and force plate gait kinetics in sound Warmbloods at walk and trot." The Veterinary Journal **186**(3): 347-351.

Parkes, R. S., Weller, R., Groth, A. M., May, S., Pfau, T. (2009). "Evidence of the development of 'domain-restricted' expertise in the recognition of asymmetric motion characteristics of hindlimb lameness in the horse." Equine Veterinary Journal **41**(2): 112-117.

Parsons, K. and A. Wilson (2006). "The use of MP3 recorders to log data from equine hoof mounted accelerometers." Equine Veterinary Journal **38**(7): 675-680.

Parsons, K. J., Pfau, T., Wilson, A. M. (2008) *a.* "High-speed gallop locomotion in the Thoroughbred racehorse. I. The effect of incline on stride parameters" Journal of Experimental Biology **211**(6): 935-944.

Parsons, K. J., Pfau, T., Wilson, A. M. (2008) *b*. "High-speed gallop locomotion in the Thoroughbred racehorse. II. The effect of incline on centre of mass movement and mechanical energy fluctuation." Journal of Experimental Biology **211**(6): 945-956.

Pfau, T., Witte, T. H., Wilson, A. M. (2005). "A method for deriving displacement data during cyclical movement using an inertial sensor." Journal of Experimental Biology **208**(13): 2503-2514.

Pfau, T., Witte, T. H., Wilson, A. M. (2006). "Centre of mass movement and mechanical energy fluctuation during gallop locomotion in the Thoroughbred racehorse." Journal of Experimental Biology **209**(19): 3742-3757.

Pfau, T., Starke, S., Tröster, S., Roepstorff, L. (2013). "Estimation of vertical tuber coxae movement in the horse from a single inertial measurement unit." The Veterinary Journal **198:** 498-503

Ratzlaff, M. H., Wilson, P. D., Hutton, D. V., Slinker, B. K. (2005). "Relationships between hoof-acceleration patterns of galloping horses and dynamic properties of the track." American Journal of Veterinary Research **66**(4): 589-595.

Rentschler, I., Jüttner, M., Unzicker, A., Landis, T. (1999). "Innate and learned components of human visual preference." Current Biology **9**(13): 665-671.

Rogers, C. W. and E. C. Firth (2004). "Musculoskeletal responses of 2-year-old Thoroughbred horses to early training. 2. Measurement error and effect of training stage on the relationship between objective and subjective criteria of training workload." New Zealand Veterinary Journal **52**(5): 272-279.

Rollet, Y., Lecuyer, E., Chateau, H., (2004). "Development of a 3D model of the equine distal forelimb and of a GRF shoe for noninvasive determination of in vivo tendon and ligament loads and strains." Equine Veterinary Journal **36**: 677

Ross M, and Dyson S, (2003). In Ross, M. W., Dyson, S. J., editors: *Diagnosis and management of lameness in the horse.* 1st ed. St. Louis: Saunders p15, in *Chapter 15 The Athletic Horse 2nd edition (2014), Hodgson, D. R., McKeever, K. H., McGowan, C. M., Elsevier Saunders, Missouri*

Schaer, B. D., Ryan, C.T., Boston, R.C., Nunamaker, D.M. (2006). "The horse-racetrack interface: a preliminary study on the effect of shoeing on impact trauma using a novel wireless data acquisition system." Equine Veterinary Journal **38**(7): 664-670.

Setterbo, J. J., Garcia, T. C., Campbell, I. P., Reese, J. L., Morgan, J. M., Kim, S. Y., Hubbard, M., Stover, S. M. (2009). "Hoof accelerations and ground reaction forces of Thoroughbred racehorses measured on dirt, synthetic, and turf track surfaces." American Journal of Veterinary Research **70** (10): 1220-1229.

Singer, E. R., Barnes, J., Saxby, F., Murray, J. K. (2008). "Injuries in the event horse: Training versus competition." The Veterinary Journal **175**(1): 76-81.

Sloet van Oldruitenborgh-Oosterbaan, M. M., Barneveld, A., Schamhardt, H. C. (1997). "Effects of treadmill inclination on kinematics of the trot in Dutch Warmblood horses." Equine Veterinary Journal **29**(S23): 71-75.

Starke, S. D., Witte, T. H., May, S. A., Pfau, T. (2012). "Accuracy and precision of hind limb foot contact timings of horses determined using a pelvis-mounted inertial measurement unit." Journal of Biomechanics **45**(8): 1522-1528.

Steins, D, 2014, personal communication

Thomsen, M. H., Persson, A. B., Jensen, A. T., Sorensen, H., Andersen, P. H. (2010). "Agreement between accelerometric symmetry scores and clinical lameness scores during experimentally induced transient distension of the metacarpophalangeal joint in horses." Equine Veterinary Journal **42**: 510-

515.

Viñuela-Fernández, I., Jones, E., Chase-Topping, M. E., Price, J. (2011). "Comparison of subjective scoring systems used to evaluate equine laminitis." The Veterinary Journal **188**(2): 171-177.

Wagner, A. E. (2010). "Effects of Stress on Pain in Horses and Incorporating Pain Scales for Equine Practice." Veterinary Clinics of North America: Equine Practice **26**(3): 481-492.

Weishaupt, M., Wiestner, T., Hogg, H. P., Jordan, P., Auer, J. A, Barrey, E. (2001). "Assessment of gait irregularities in the horse: eye vs. gait analysis." Equine Veterinary Journal, **Supplement 33**: 135-140.

Weishaupt, M. A., Wiestner, T., von Peinen, K., Waldern, N., Roepstorff, L., Van Weeren, R., Meyer, H., Johnston, C. (2006). "Effect of head and neck position on vertical ground reaction forces and interlimb coordination in the dressage horse ridden at walk and trot on a treadmill." Equine Veterinary Journal **38, Supplement 36**: 387-392.

Witte, T., Knill, K., Wilson, A. M. (2004). "Determination of peak vertical ground reaction force from duty factor in the horse (Equus caballus)." Journal of Experimental Biology **207**(Pt 21): 3639-3648.

Witte, T. H., Hirst, C. V., Wilson, A. M. (2006). "Effect of speed on stride parameters in racehorses at gallop in field conditions." Journal of Experimental Biology **209**(21): 4389-4397.