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PII: S1090-0233(18)30006-6
DOI: https://doi.org/10.1016/j.tvjl.2018.01.006
Reference: YTVJL 5105

To appear in:

Accepted date: 24-1-2018

Please cite this article as: Filipe M.Serra Bragança, Marie Rhodin, Paul René van Weeren, On the brink of daily clinical application of objective gait analysis: What evidence do we have so far from studies using an induced lameness model? (2010), https://doi.org/10.1016/j.tvjl.2018.01.006

Review

On the brink of daily clinical application of objective gait analysis: What evidence do we have so far from studies using an induced lameness model?

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Highlights

- Quantitative gait analysis offers objective and unbiased information which can be valuable during a lameness examination.
- Kinetic and kinematic methods can be used to quantify changes in locomotion due to lameness.
- Gait analysis using optical motion capture and inertial motion unit sensors have good potential for clinical application.
- Repeated measurements (e.g. before and after diagnostic anaesthesia or treatment) may have highest clinical relevance.

Abstract

Quantitative gait analysis has the potential to offer objective and unbiased gait information that can assist clinical decision-making. In recent years, a growing number of gait analysis systems have come onto the market, highlighting the demand for such technology in equine orthopaedics. However, it is imperative that the measured variables which are used as outcome parameters are supported by scientific evidence and that the interpretation of such measurements is backed by a proper understanding of the biomechanical principles of equine locomotion. This review, which is based on studies on experimentally induced lameness, summarises the currently most widely used methods for gait analysis and the available evidence concerning gait parameters that can be used to quantify gait changes due to lameness. These are discussed regarding their current and future potential for routine clinical application.

Keywords: Asymmetry; Gait analysis; Horse; Lameness; Motion capture.

Introduction

The primary uses of the horse as sport and leisure animal are based on the capacity of its locomotor system. Disorders of that system, which become almost invariably clinically manifest as lameness, are one of the main reasons for equine veterinary consultation (Nielsen et al., 2014). It has also been reported that equine practitioners spend most of their working time on lameness examination (Loomans et al., 2007). Lameness can affect horses from all equestrian disciplines, leading to a financial loss for horse owners, days lost in training and/or competition (Jeffcott et al., 1982; Murray et al., 2006; Dyson et al., 2008; Egenvall et al., 2008, 2013).).

In the context of this review, it is essential to define the term 'lameness' as a clinical interpretation of one or more signs indicating a pathological condition of the locomotor system (van Weeren et al., 2017). It is hence an alteration of the normal gait due to a functional or structural disorder in this system (Buchner, 2013), making it a clinical entity that is more than just a deviation of what can be seen as optimal gait. This definition of lameness challenges the veterinarian to discriminate between normal and abnormal (i.e. pathological) gait for a specific subject presented with a complaint of lameness. When confronted with animals without complaints, the challenge may be two-fold. First, to decide whether some gait irregularity and/or asymmetry is present. Second, to judge whether there is an underlying pathological condition or not, hence whether or not the irregularity/asymmetry should be considered a subclinical sign of lameness. In the majority of cases, standard practice has been and still is to accomplish this by subjective assessment of gait.

Although it is widely recognised that most gait events can be assessed efficiently by experienced clinicians through subjective visual examination (Dyson, 2014), any observer is hampered by limitations of the maximal temporal resolution of the human eye, limits to the perception of asymmetry (Parkes et al., 2009) and memorisation. Partially related to these limitations, a subjective visual evaluation suffers from some substantial drawbacks which are reflected in the low inter-observer agreement (Fuller et al., 2006; Hewetson et al., 2006; Keegan et al., 2010; Thomsen et al., 2010; McCracken et al., 2012; Keegan et al., 2013, Hammarberg et al., 2016) and the difficulty of consistent and interchangeable documentation of gait alterations. The latter is mainly due to the lack of uniformity in lameness rating scales (Wyn-Jones, 1988; AAEP, 1999; Dyson, 2011; Ross, 2013). A detailed overview of the limitations of subjective lameness assessment can be found in the review of Keegan (2007).

There is also a potential bias in the interpretation of nerve/joint blocks (Arkell et al., 2006), which can be aggravated by false positive and false negative results (Schumacher et al., 2014). An additional confounding issue may be the effect of nerve blocks in sound horses, although the few studies available (Kübber et al., 1994; Keegan et al., 1997; Drevemo et al., 1999; Liedtke et al. 2012) have reported somewhat contradictory results (Van de Water et al., 2016), and further investigation of the effect of diagnostic analgesia in sound horses is warranted.

These issues complicate lameness examinations and form confounding factors affecting clinical decision-making and hampering clinical orthopaedic research on the evaluation of diagnostic procedures, treatments and rehabilitation protocols.

Long restricted to sophisticated gait labs due to financial and practical constraints, measurement systems for equine gait are becoming more affordable and practically applicable, paving the way for routine application in daily clinical practice. This development raises new issues about the reliability of available systems and the validity and usefulness of the output of such systems. This review aims to summarise and critically evaluate current evidence related to methods of objective gait analysis in horses. This review is limited to techniques of gait analysis with potential for practical daily use in a clinical setting, of which evidence regarding the relevant outcome parameters and the applications and limitations are discussed. The emphasis is on data regarding objective gait parameters associated with lameness based on induced lameness models and the interpretation of objective gait assessment measurements. Essential areas for future development are also identified.

Searches

PubMed and Google Scholar were used as search engines to find suitable references for this review. The terms ‘horse’ and ‘equine’ were used in combination with the keywords ‘kinematics’, ‘kinetics’, ‘gait analysis’, ‘motion capture’, ‘objective lameness’, ‘lameness’, ‘force plate’, ‘pressure plate’, ‘treadmill’, ‘sensor’, ‘IMU’, ‘inertial measurement unit’, ‘agreement’, ‘assessment’, ‘observer’. Articles were first selected based on their relevance to the topic of this review. Only manuscripts in the field of equine gait analysis were selected; studies using quantitative gait analysis tools for purposes other than lameness evaluation were excluded, as well as studies using theoretical models of lameness. Subsequently, the references in all selected articles were screened for further possibly relevant articles. As our purpose was the identification of the best parameters to give information about lameness, the majority of studies concerned experimental studies in which lameness was induced. This eliminated bias from possible multi-limb lameness, any disagreement regarding the exact location of pain, or inconsistencies of diagnostic methods to correctly identify the lame limb(s), as often encountered in clinical studies. No meta-analysis or statistical analysis was performed; this article constitutes a descriptive review.

Measuring techniques for objective gait assessment based on quantification of either forces (kinetics) or motion (kinematics)

Kinetics

In kinetic studies, the internal and external forces resulting from musculoskeletal work are analysed. The stationary force measuring platforms were among the first instruments used for objective lameness assessment (Morris and Seeherman, 1987; Aviad, 1988; Merkens and Schamhardt, 1988a) and are still considered as the 'gold standard' for kinetic gait analysis and the detection of (weight-bearing) lameness. They measure the three components in which the ground reaction force (GRF) can be decomposed in a Cartesian coordinate system. Force plates are precise and accurate instruments, but the data collection process is laborious and time-consuming.

Pressure measuring plates (van Heel et al., 2004) overcome some of these limitations by allowing collection of consecutive strides (if plate size is appropriate) and detailed mapping of the force distribution underneath the hoof. However, the sensors of a pressure plate cannot decompose the GRF in the three constituting elements and outcome will to a certain extent be influenced by shear forces as well. Furthermore, pressure plates are not as accurate and precise as force plates that use piezoelectric sensors (Oosterlinck et al., 2010) and this might be due to the lower sampling frequencies when compared to force plates and in some extent, to sensor activation thresholds (Oosterlinck et al., 2012). An alternative to force or pressure plates is the force measuring horseshoe. This idea dates from the late 50's (Björck, 1958), but was only further developed in the 90's (Roepstorff and Drevemo, 1993). Several types of force shoes have been developed and have been used successfully for measuring ground reaction forces (Kai et al., 2000), however, in most cases, size and weight of the shoe were critical limiting factors for their clinical applicability. More recently, a more advanced, lighter version has been used successfully during athletic activity (Munoz-Nates et al., 2015), but the technology is not yet widely available.

An attempt to overcome most of the limitations associated with stationary force plates was the development of a force measuring treadmill (Weishaupt et al., 2002), which allows measurements of consecutive strides of all four limbs simultaneously. The method enables accurate, quick and practical determination of GRF, but is only available in one specialised lab (University of Zurich, Switzerland), solely measures the vertical GRF and requires horses being accustomed to locomotion on a treadmill.

Overall, the currently available kinetic methods for the assessment of lameness are not ready for widespread clinical application, due to complexities in data collection and analysis. Hence, there is a need to develop measuring systems for quantifying kinetics in a clinical setting. In the meantime, the existing methods remain highly valued tools for researchers in the field of equine gait analysis.

Kinematics

Kinematics is the study of the movement of body segments during locomotion. The movement can be described as the displacement/velocity/acceleration as a function of time, of a body segment relative to a reference coordinate system, or it can represent the relation (i.e. angle) between body segments. Since their development, serial photography and cine film were almost immediately used for equine gait analysis (van Weeren, 2013) and in the so-called modern era of equine gait analysis, high speed film was the first technique used for recording equine locomotion using reflective skin markers, initially based on twodimensional (2D) analysis (Fredricson and Drevemo, 1971). Further technological developments led to the introduction of more sophisticated methods of gait analysis (Kastner et al., 1990; van Weeren et al., 1990b) that allowed for higher recording speeds (up to 300Hz) in three dimensions (3D). Nowadays, the most widely used systems are the Oqus/Qhorse (Qualisys AB) system, the Vantage (Vicon) system and the Motion Analysis (Motion Analysis Systems) system. Three-dimensional optical motion capture (OMC) uses several (mostly infrared) cameras positioned around a calibrated measuring volume and records and automatically tracks the position of several reflective markers simultaneously, correcting for perspective and distortion errors and other artefacts that might influence single-camera 2D systems. The 3D systems are highly accurate and precise and are therefore considered the ‘gold standard’ for kinematic analysis.

Studies on equine kinematics using OMC have initially often been carried out on a treadmill due to the limited field of view of the cameras, but nowadays there are several locations where camera systems are used for the capture of overground locomotion. OMC using skin markers is affected by skin displacement artefacts due to the displacement of the skin over the skeletal structures that are in most cases the real objects of the measurements. This artefact depends mainly on the location on the body, being almost negligible in the distal limb but being large in the proximal parts of the limb where for example the greater trochanter of the femur may move over a range of up to 15 cm under the skin (van Weeren et al., 1988, 1990a). However, this is less important in comparative studies, as it affects horses of similar size and conformation to the same extent. For studies in which absolute values are essential, skin displacement correction algorithms have been developed (van den Bogert et al., 1990). More recently, low pass Butterworth filters (Sinclair et al., 2013) have been used to remove soft tissue artefacts since correction algorithms are subject- and task-specific and therefore not universally applicable.

Around the same time the use of OMC became more common in equine gait analysis, another method of kinematic analysis based on body mounted accelerometers was reported (Kastner, 1989). The technology relies on sensors attached to body segments and recording data on acceleration during locomotion. This technique allows gait analysis during overground locomotion without the need for costly infrastructure, making these systems very versatile. The development of this technology has been boosted by the introduction of microelectromechanical systems (MEMS) and the introduction of miniature wireless accelerometers (Keegan et al., 2011), permitting the fabrication of more complex inertial measurement units (IMUs) (Pfau et al., 2005). These instruments provide objective gait information calculated from acceleration data (Barrey et al., 1994), or acceleration data can be double integrated to estimate displacement. However, IMU sensors are prone to integration errors that may accumulate (i.e. drift), making these instruments less and less accurate as the measurement progresses. This can be accounted for by attitude and heading reference systems (AHRS), periodically re-setting the gyroscope during cyclical movements, by advanced filters (e.g. a Kalman filter (Kalman et al., 1960)) and, if measuring outdoors, by global positioning system (GPS) data. Nevertheless, these systems are less accurate and precise compared with OMC measuring displacement, although they are more accurate and reliable than OMC when measuring acceleration (Clayton and Schamhardt, 2013; Peham, 2013). Despite these well-known limitations, they may be a practical, mobile and user-friendly solution with suitable potential for practical daily clinical use.

In conclusion, OMC and IMU technology can successfully measure overground locomotion. However, OMC needs several cameras to cover several strides during one run. IMU systems are attached to the horse and can hence record many continuous strides, but they are less accurate than OMC for determining an absolute position.

Kinetic and kinematic parameters associated with lameness

There is extensive evidence regarding the association between individual gait parameters and lameness (Table 1-3), but there are some inconsistencies between publications, leading to divergence concerning the assessment of the significance of some of these gait changes for lameness evaluation. Several factors may contribute to this, such as difficulty in assessing the level of pain experienced by the horse, different methodologies to measure specific parameters, differences in study design, in lameness model and differences between treadmill and overground locomotion (Barrey et al., 1993; Buchner et al., 1994; Gómez Álvarez et al., 2009). However, in general, the evidence is robust with a clear association between lameness and changes for several gait parameters at the trot.

Kinetics and temporal stride parameters

In unilateral lameness at the trot, the most commonly reported changes measured in the lame limb are a reduction of peak vertical force, vertical impulse (Fig. 1) and decreased swing duration (Table 1), although swing duration is reduced in all limbs. The horizontal forces during the stance phase, described as breaking and propulsion forces, are also affected by lameness, with the reduction of peak breaking force reported as the most consistently altered parameter due to lameness (Morris and Seeherman, 1987; Keg et al., 1994; Clayton et al., 2000; Ishihara et al., 2005).

Stance duration has been reported to decrease, but this was only observed in studies using the shoe pressure model for transient lameness induction (Merkens and Schamhardt, 1988b), suggesting that the location of pain might influence the observed gait adaptation mechanisms.

Some kinetic variables of the non-lame limbs are also affected to a certain extent, as a consequence of compensatory mechanisms in gait adaptation to lameness (Weishaupt, 2008).

Kinematics

Most research has focused on the kinematic analysis of head and pelvis movement, back motion and temporal and angular changes in limb motion. Although the first reports on symmetry parameters to quantify lameness were based on acceleration measurements (Kastner, 1989; Kastner et al., 1990), research in the last two decades has focussed more on measurements of vertical displacement, probably since interpretation of displacement data is more intuitive and closer to the commonly observed parameters during visual lameness assessment than acceleration or speed (Fig. 1).

At the trot in a straight line, the head, withers and pelvis of non-lame horses move upwards and downwards twice during the stride cycle, generating a typical sinusoidal pattern. In the presence of lameness, this sinusoidal pattern becomes asymmetrical and, by measuring the specific changes in the vertical displacement curves, lameness can be quantified objectively (Buchner et al., 1996a) (Fig. 1).

With increasing lameness, the amplitude of the vertical displacement during the stance phase of the lame limb decreases, while the amplitude of the contralateral limb increases (Buchner et al., 1996a). This can be measured as the difference of the amplitude of the vertical displacement, or as a symmetry index between contralateral steps (Fig. 1; Table 2).

Due to this change in the amplitude of the vertical displacement during the stance phase of a lame limb, the head/withers and pelvis reach a minimum position that is higher when compared with the contralateral non-lame limb, resulting in a difference between minimum positions (MinDiff) (Table 2) of either the head/withers or the pelvis in case of fore or hind limb lameness, respectively (Fig. 1). The head/withers or pelvis also reaches a maximum position at the end of the swing phase just before hoof contact with the ground and again at the end of the stance phase (Buchner et al., 1996a; Starke et al., 2012b). During lameness, the maximum positions of the head and pelvis at the end of the stance phase of the lame limb are also lower when compared to the non-lame limb, resulting in a difference between maximum positions (MaxDiff) (Table 2) of the head/withers or pelvis in case of fore or hind limb lameness, respectively (Buchner et al., 1996a; Keegan et al., 2004)

The relation between MinDiff, MaxDiff and ground reaction forces has also been investigated for horses with hind limb lameness. It has become clear from force plate measurements in lame horses that MinDiff reflects the difference in vertical ground reaction forces and MaxDiff the differences in horizontal forces between limbs (Bell et al., 2016). However, kinetic analysis remains most discriminative for supporting limb lameness and, the authors stated that the kinematic parameters MaxDiff and MinDiff cannot be used to replace measurements of vertical and horizontal forces (Bell et al., 2016).

Compensatory movements of adaptation to lameness have also been reported for kinematic parameters (Kelmer et al., 2005; Rhodin et al., 2013) (Fig. 2), wherein primary (induced) hind limb lameness, a compensatory head nod resembling a forelimb lameness in the ipsilateral forelimb has been described (Buchner et al., 1996a; Kelmer et al., 2005). On the other hand, in case of a primary (induced) forelimb lameness, compensatory movements have been described in both the ipsilateral and contralateral hind limbs (Buchner et al., 1996a; Kelmer et al., 2005). The compensatory head movement due to a primary hind limb lameness is more pronounced than the compensatory movement in the pelvis caused by a primary forelimb lameness (Rhodin et al., 2013).

In forelimb lameness, the parameters associated with vertical head displacement have been reported to be affected more importantly than those associated with the vertical displacement of the withers (Buchner et al., 1996a). This may be true with respect to the magnitude of the effect, but there is indeed an effect on wither motion (Uhlir et al., 1997; Kelmer et al., 2005), and recent work (Persson Sjödin et al., 2016) showed that withers' movement might be used to differentiate between head movement asymmetries resulting from a primary forelimb or a primary hind limb lameness. Horses with primary forelimb lameness show ipsilateral head and withers asymmetry (so pointing towards the same side as being lame), while in horses with primary hind limb lameness, the compensatory asymmetry of head is contralateral to the asymmetry of the withers (so both pointing towards a different side as being lame, with the withers asymmetry indicating the lame diagonal and the head asymmetry suggesting the non-lame diagonal (Persson Sjödin et al., 2016). Nevertheless, in case of subtle lameness, the symmetry of withers' movement might not be affected (Buchner et al., 1996a).

Regarding thoracolumbar movement, a change in the range of motion (ROM) of back segments in horses with induced back pain at trot has been reported (Table 2). In one study, it was observed that unilateral pain in the longissimus dorsi muscle provoked increased flexion-extension and lateral bending of the back at the trot (Wennerstrand et al., 2009). However, the reported changes in back motion are not very prominent, and further studies are needed to fully understand how back pain may affect back kinematics. In case of primary forelimb lameness at the trot, an increase of back ROM for flexion-extension and a reduction of lateral bending has been reported (Gómez Álvarez et al., 2007). In horses with primary hind limb lameness at the trot, only a reduction of ROM for flexion-extension was reported (Gómez Álvarez et al., 2008). Nevertheless, the currently commercially available clinical gait analysis systems do not generate data on back-specific parameters, and further development of the methodology for the specific assessment of back function is urgently needed.

Apart from asymmetries, changes in the motion pattern of the individual limb due to lameness have also been reported (Table 3). The most consistently described changes in case of lameness induced in joints are reductions in stride duration, fetlock extension and in joint ROM (Table 3). Moreover, there is also an increase of relative stance duration, as a percentage of stride duration (Keegan et al., 2000; Weishaupt et al., 2006; Buchner et al., 2010).

The available evidence on objective kinematic parameters during lunging is scarce, with one study on induced lameness reporting an increase in the minimum pelvic height difference (PDmin) when the lame hind limb was on the inside of the circle, compared with the measurements on a straight line (Rhodin et al., 2013). More studies are needed to better understand the circle-dependent changes in the measured kinematic parameters of horses with different causes of lameness. The situation is more complicated than on the straight line, as circular movements such as lunging induce asymmetrical kinematic patterns by itself (Starke et al., 2012a; Pfau et al., 2014; Rhodin et al., 2015; Greve and Dyson, 2016; Greve et al., 2017) and because the magnitude of these effects depends on the speed and diameter of the circle (Pfau et al., 2012b).

The interpretation of asymmetries detected by quantitative gait analysis

Most of currently used objective gait analysis methods rely on gait symmetry measurements. In this respect, it is important to question whether or not asymmetry is invariably a sign of lameness. Whereas the relationship between unilateral pain induction and the consequential occurrence of kinematic asymmetry has been demonstrated multiple times (Peloso et al., 1993; Barrey et al., 1994; Buchner et al., 1996a, 1996b; Peham et al., 1996; Keegan et al., 2001, 2000; Kramer et al., 2004; Kelmer et al., 2005; Rhodin et al., 2013; Tóth et al., 2014; Persson Sjödin et al., 2016), the inverse relationship has not yet been investigated and the question if and to what extent small measurable asymmetries can be directly attributed to pain has not been answered so far. Furthermore, movement asymmetries may not be evident in horses with bilateral lameness and lameness may only become apparent after unilateral diagnostic analgesia.

The issue is not limited to the outcome of objective gait analysis since some reports suggest that up to 75% of horses in regular work are lame when subjected to a rigorous subjective lameness exam (Dyson and Greve, 2016). Using an objective gait analysis system, Rhodin et al. (2017) found that a large proportion (72.5%) of 222 horses presented significant movement asymmetries. In another study, 47% of 201 riding horses in training, which were all perceived as free from lameness by their owner, showed movement asymmetries at the trot in a straight line, above previously reported asymmetry thresholds (Rhodin et al., 2015). If all these horses would have underlying pathology indeed, this may be considered a severe welfare problem, but, as said, it remains to be established if all visible or measurable asymmetries are indeed caused by orthopaedic pain. Nevertheless, it has been demonstrated clinically (Maliye et al., 2013, 2015, 2016) and experimentally (Tóth et al., 2014; Hoerdemann et al., 2017) that measurable movement asymmetries can successfully respond to diagnostic anaesthesia.

It is therefore of utmost importance to investigate the relation between (mild) gait asymmetries and pain using objective parameters for both conditions. It should be stressed that at this moment, objective gait analysis systems only measure gait asymmetry and do not establish whether this asymmetry is due to an underlying pathological process. Moreover, it should be emphasised that objective gait analysis gives valuable additional information to the clinician that can help in decision-making, but does not and cannot replace the expertise of a veterinarian, who will make a final evaluation and decide whether the asymmetry that was detected should be labelled ‘lameness’ or not (Fig. 3) (van Weeren et al., 2017).

Practical handling of information from objective gait analysis in a research or clinical setting

When performing objective gait analysis, the results can be interpreted and analysed in a variety of ways. First, the gait parameters can be compared with a ‘standard horse’, i.e. an average of a sample being as representative as possible for the population. Although this approach is simple and commonly used for example in clinical chemistry, it might be less suitable for the interpretation of gait analysis information due to the considerable individual variation in most kinematic parameters. When the inter-individual biological variation is more prominent than the variation induced by lameness in an individual horse, this approach will not work. Also, this method is affected by differences in kinematic and kinetic parameters due to individual differences in preferred speed (Khumsap et al., 2001; Weishaupt et al., 2010a; Pfau et al., 2012a; Starke et al., 2013) and in conformation.

Second, gait parameters can be compared using repeated measurements of absolute kinetic/kinematic parameters of the same subject over time, or after interventions (e.g. diagnostic anaesthesia). Whereas this approach assumes the availability of baseline data, which is not always the case in horses presented for lameness, unless the situation after application of diagnostic anaesthesia is used as such, it does not suffer from the problems mentioned above. The approach could be very time consuming for some methods of gait analysis (e.g. force plate analysis), but this is not an issue for more recent automated techniques that are becoming increasingly available (e.g. IMU and OMC). This approach can also be affected by inter-trial differences in speed which may influence several gait parameters (Weishaupt et al., 2010a).

Third, an alternative method that tries to overcome most of the problems mentioned above is the comparison between left and right steps and the calculation of asymmetry between both sides (i.e. left vs right), since all quadrupedal vertebrates are expected to exhibit bilateral movement symmetry within limb pairs (i.e. forelimb pair and hind limb pair) (Abourachid, 2003). This approach is less affected by inter-trial variation, since both sides are compared on a stride-to-stride basis, and is not affected by the within-horse variation since the measured horse is always its own control. Although this method eliminates the between-horse variation and minimises some of the inter-trial variation, it might fail to detect gait changes in cases of bilateral or even more complex multi-limb lameness (Ratzlaff et al., 1982; Buchner et al., 1995; Pourcelot et al., 1997; Serra Bragança et al., 2016), depending on the bi-or unilateral expression of compensatory mechanisms. Moreover, this method may not be suitable for assessment on a circle, by differences in circle diameter and speed (Pfau et al., 2012a).

Further, the approach is only valid for naturally symmetrical gaits (walk, trot, pace) and has thus far only been used for lameness assessment at unridden trot, on a straight line or during lunging (Peloso et al., 1993; Barrey et al., 1994; Buchner et al., 1996a, 1996b, Peham et al., 1996; Keegan et al., 2000, 2001; Kramer et al., 2004; Kelmer et al., 2005; Rhodin et al., 2013; Tóth et al., 2014; Persson Sjödin et al., 2016).

As mentioned earlier, the challenge of using asymmetry measurements is to determine whether the measured asymmetry is caused by any underlying pathology or should be seen as the trait of a particular individual. Previous studies have used thresholds to determine whether horses should be deemed lame or not based on the measured asymmetry (Keegan et al., 2012, 2013). However, thresholds are based on limited reference populations and depend on the bandwidth chosen. Therefore, they may well represent the population as a whole but may present limitations for the evaluation of an individual case. This warning against the indiscriminate application of such thresholds to judge a horse sound or lame has been recently raised (van Weeren et al., 2017). A combination of repeated measurements of asymmetry (e.g. before and after a diagnostic anaesthesia/intervention) might provide the best information for research and clinical use. Another example is the use of repeated measurements before and after flexion tests to objectify the response to such provocations (Marshall et al., 2012; Starke et al., 2012c).

Another critical factor that poses a challenge when interpreting repeated measurements from the same horse is the effect of inter-trial variation due to differences in subject demeanour and speed. However, although speed is known to influence many of the measured kinetic and kinematic parameters (Khumsap et al., 2001; Weishaupt et al., 2010a; Pfau et al., 2012a; Starke et al., 2013), the effect of increased speed appears to only slightly affect the measured movement asymmetry during trot at a straight line, whilst during the subjective lameness assessment, increased speed can lead to the erroneous classification of lame horses as sound (Starke et al., 2013).

In summary, although with some constraints, there is sufficient evidence to support the use of objective gait analysis during lameness assessment in research and in a clinical setting. It is important to stress that the technology should be used as a tool supporting the clinician formulating an evidence-based diagnosis, prognosis and/or therapeutic plan, and not as an infallible guideline that should be obeyed. The incorporation of this technology is not much different from the establishment of advanced imaging technology in the orthopaedic workup of horses. However, clinical expertise will remain paramount and decisive in the final decision making in equine orthopaedics.

Conclusions

We have reached the stage that kinematic analysis techniques have developed far enough regarding reliability and practicality to warrant regular clinical application. It is hence justified to incorporate objective gait analysis in the daily clinical assessment of lameness using state-of-the-art sensor or OMC-based gait analysis systems. The approach offers veterinarians an objective method to quantify gait and can be extremely relevant, especially in cases of mild lameness and as an invaluable aid in the comparison/interpretation of repeated measurements between interventions (e.g. diagnostic anaesthesia and flexion tests). It can be anticipated that objective gait quantification techniques will become standard procedures for the longitudinal monitoring of sound and lame horses, and for accurate and unambiguous documentation of gait evaluation data.

Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

References:

AAEP, 1999. Guide to veterinary services for horse shows, Seventh Edn. American Association of Equine Practitioners, Lexington, Ky.

Abourachid, A., 2003. A new way of analysing symmetrical and asymmetrical gaits in quadrupeds. Comptes Rendus Biologies 326, 625–630.

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. The Veterinary Record 159, 346–349.

Aviad, A.D., 1988. The use of the standing force plate as a quantitative measure of equine lameness. Journal of Equine Veterinary Science 8, 460–462.

Barrey, E., Galloux, P., Valette, J.P., Auvinet, B., Wolter, R., 1993. Stride characteristics of overground versus treadmill locomotion in the saddle horse. Acta Anatomica 146, 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 (Suppl. 17), 7–12.

Bell, R.P., Reed, S.K., Schoonover, M.J., Whitfield, C.T., Yonezawa, Y., Maki, H., Pai, P.F., Keegan, K.G., 2016. Associations of force plate and body-mounted inertial sensor measurements for identification of hind limb lameness in horses. American Journal of Veterinary Research 77, 337–345.

Björck, G., 1958. Studies on the draught force of horses. Development of a method using strain gauges for measuring forces between hoof and ground. Acta Agriculturæ Scandinavica 8. (Suppl. 4), 1–109.

Buchner, H.H.F., Savelberg, H.H., Schamhardt, H.C., Merkens, H.W., Barneveld, A, 1994. Kinematics of treadmill versus overground locomotion in horses. The Veterinary Quarterly 16 (Suppl. 2), 87–90.

Buchner, H.H.F., Savelberg, H.H., Schamhardt, H.C., Barneveld, A., 1995. Bilateral lameness in horses-a kinematic study. The Veterinary Quarterly 17, 103–105.

Buchner, H.H.F., Savelberg, H.H., Schamhardt, H.C., Barneveld, A., 1996a. Head and trunk movement adaptations in horses with experimentally induced fore- or hindlimb lameness. Equine Veterinary Journal 28, 71–76.

Buchner, H.H.F., Savelberg, H.H., Schamhardt, H.C., Barneveld, A., 1996b. Limb movement adaptations in horses with experimentally induced fore- or hindlimb lameness. Equine Veterinary Journal 28, 63–70.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C., Barneveld, A., 2010. Temporal stride patterns in horses with experimentally induced fore- or hindlimb lameness. Equine Veterinary Journal 27, 161–165.

Buchner, H.H.F., 2013. Gait adaptation in lameness, in: Clayton, H.M., Back, W. (Eds.), Equine Locomotion. Second Edn. Saunders Elsevier, St. Luis, MO, USA, p. 175.

Clayton, H.M., Schamhardt, H.C., Willemen, M.A., Lanovaz, J.L., Colborne, G.R., 2000. Kinematics and ground reaction forces in horses with superficial digital flexor tendinitis. American Journal of Veterinary Research 61, 191–196.

Clayton, H.M., Schamhardt, H.C., 2013. Measurement techniques for gait analysis, in: Clayton, H.M., Back, W. (Eds.), Equine Locomotion, Second Edn. Saunders Elsevier, St. Luis, MO, USA, pp. 31–60.

Drevemo, S., Johnston, C., Roepstorff, L., Gustås, P., 1999. Nerve block and intra-articular anaesthesia of the forelimb in the sound horse. Equine Veterinary Journal 31 (Suppl. 30), 266–269.

Dyson, P.K., Jackson, B.F., Pfeiffer, D.., 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, 650–657.

Dyson, S., 2011. Can lameness be graded reliably? Equine Veterinary Journal 43, 379–382.

Dyson, S., 2014. Recognition of lameness: Man versus machine. The Veterinary Journal 201, 245–248.

Dyson, S., Greve, L., 2016. Subjective gait assessment of 57 sports horses in normal work: a comparison of the response to flexion tests, movement in hand, on the lunge and ridden. Journal of Equine Veterinary Science 38, 1–7.

Egenvall, A., Bonnett, B., Wattle, O., Emanuelson, U., 2008. Veterinary-care events and costs over a 5-year follow-up period for warmblooded riding horses with or without previously recorded locomotor problems in Sweden. Preventive Veterinary Medicine 83, 130–143.

Egenvall, A., Tranquille, C.A., Lönnell, A.C., Bitschnau, C., Oomen, A., Hernlund, E., Montavon, S., Franko, M.A., Murray, R.C., Weishaupt, M.A.,et al., 2013. Days-lost to training and competition in relation to workload in 263 elite show-jumping horses in four European countries. Preventive Veterinary Medicine 112, 387–400.

Fredricson, I., Drevemo, S., 1971. A new method of investigating equine locomotion. Equine Veterinary Journal 3, 137–140.

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, 281–286.

Gómez Álvarez, C.B., Wennerstrand, J., Bobbert, M.F., Lamers, L., Johnston, C., Back, W., van Weeren, P.R., 2007. The effect of induced forelimb lameness on thoracolumbar kinematics during treadmill locomotion. Equine Veterinary Journal 39, 197–201.

Gómez Álvarez, C.B., Bobbert, M.F., Lamers, L., Johnston, C., Back, W., van Weeren, P.R., 2008. The effect of induced hindlimb lameness on thoracolumbar kinematics during treadmill locomotion. Equine Veterinary Journal 40, 147–152.

Gómez Álvarez, C.B., Rhodin, M., Byström, a, Back, W., van Weeren, P.R., 2009. Back kinematics of healthy trotting horses during treadmill versus over ground locomotion. Equine Veterinary Journal 41, 297–300.

Greve, L., Dyson, S., 2016. Body lean angle in sound dressage horses in-hand, on the lunge and ridden. The Veterinary Journal 217, 52–57.

Greve, L., Pfau, T., Dyson, S., 2017. Thoracolumbar movement in sound horses trotting in straight lines in hand and on the lunge and the relationship with hind limb symmetry or asymmetry. The Veterinary Journal 220, 95–104.

Hammarberg, M., Egenvall, A., Pfau, T., Rhodin, M., 2016. Rater agreement of visual lameness assessment in horses during lungeing. Equine Veterinary Journal 48, 78–82.

Hewetson, M., Christley, R.M., Hunt, I.D., Voute, L.C., 2006. Investigations of the reliability of observational gait analysis for the assessment of lameness in horses. Veterinary Record 158, 852–857.

Hoerdemann, M., Smith, R.L., Hosgood, G., 2017. Duration of action of mepivacaine and lidocaine in equine palmar digital perineural blocks in an experimental lameness model. Veterinary Surgery 46, 986–993.

Ishihara, A., Bertone, A.L., Rajala-Schultz, P.J., 2005. Association between subjective lameness grade and kinetic gait parameters in horses with experimentally induced forelimb lameness. American Journal of Veterinary Research 66, 1805–1815.

Jeffcott, L.B., Rossdale, P.D., Freestone, J., Frank, C.J., Towers-Clark, P.F., 1982. An assessment of wastage in thoroughbred racing from conception to 4 years of age. Equine

Veterinary Journal 14, 185–198.

Kai, M., Aoki, O., Hiraga, A., Oki, H., Tokuriki, M., 2000. Use of an instrument sandwiched between the hoof and shoe to measure vertical ground reaction forces and three-dimensional acceleration at the walk, trot, and canter in horses. American Journal of Veterinary Research 61, 979–985.

Kalman, R.E., 1960. A new approach to linear filtering and prediction problems. Journal of Basic Engineering 82, 35–45.

Kastner, J., 1989. Bewegungsmessung auf dem weg zur klinischen methode. Osterreich Hochschulzeitung 9, 15–16.

Kastner, J., Knezevic, P.F., Girtler, D., Toeltsch, M., 1990. Die 3-dimensionale bewegungsanalyse als klinische methode zur objektivierung von lahmheiten beim pferd. Biomedizinische Technik/Biomedical Engineering 35, 171–172.

Keegan, K.G., Wilson, D.J., Wilson, D.A., Frankeny, R.L., Loch, W.E., Smith, B., 1997. Effects of anesthesia of the palmar digital nerves on kinematic gait analysis in horses with and without navicular disease. American Journal of Veterinary Research 58, 218–223.

Keegan, K.G., Wilson, D.A., Smith, B.K., Wilson, D.J., 2000. Changes in kinematic variables observed during pressure-induced forelimb lameness in adult horses trotting on a treadmill. American Journal of Veterinary Research 61, 612–619.

Keegan, K.G., Pai, P.F., Wilson, D.A, Smith, B.K., 2001. Signal decomposition method of evaluating head movement to measure induced forelimb lameness in horses trotting on a treadmill. Equine Veterinary Journal 33, 446–451.

Keegan, K.G., Yonezawa, Y., Pai, F., Wilson, D.A., Kramer, J., 2004. Evaluation of a sensor-based system of motion analysis for detection and quantification of forelimb and hind limb lameness in horses. American Journal of Veterinary Research 65, 665–670.

Keegan, K.G., 2007. Evidence-based lameness detection and quantification. Veterinary Clinics of North America: Equine Practice 23, 403–423.

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., et al., 2010. Repeatability of subjective evaluation of lameness in horses. Equine Veterinary Journal 42, 92–97.

Keegan, K.G., Kramer, J., Yonezawa, Y., Maki, H., Pai, P.F., Dent, E. V, Kellerman, T.E., Wilson, D.A., Reed, S.K., 2011. Assessment of repeatability of a wireless, inertial sensor-based lameness evaluation system for horses. American Journal of Veterinary Research 72, 1156–1163.

Keegan, K.G., MacAllister, C.G., Wilson, D.A., Gedon, C.A., Kramer, J., Yonezawa, Y., Maki, H., Pai, P.F., 2012. Comparison of an inertial sensor system with a stationary force plate for evaluation of horses with bilateral forelimb lameness. American Journal of Veterinary Research 73, 368–374.

Keegan, K.G., Wilson, D. a., Kramer, J., Reed, S.K., Yonezawa, Y., Maki, H., Pai, P.F., Lopes, M.A., 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, 17–24.

Keg, P.R., Barneveld, A., Schamhardt, H.C., van den Belt, A.J.M., 1994. Clinical and force plate evaluation of the effect of a high plantar nerve block in lameness caused by induced mid-metatarsal tendinitis. The Veterinary Quarterly 16 (Suppl. 2), 70-75.

Kelmer, G., Keegen, K.G., Kramer, J., Wilson, D.A., Pai, F.P., Singh, P., 2005. Computer-assisted kinematic evaluation of induced compensatory movements resembling lameness in horses trotting on a treadmill. American Journal of Veterinary Research 66, 646–655.

Khumsap, S., Clayton, H.M., Lanovaz, J.L., 2001. Effect of walking velocity on ground reaction force variables in the hind limb of clinically normal horses. American Journal of Veterinary Research 62, 901–906.

Khumsap, S., Lanovaz, J.L., Rosenstein, D.S., Byron, C., Clayton, H.M., 2003. Effect of induced unilateral synovitis of distal intertarsal and tarsometatarsal joints on sagittal plane kinematics and kinetics of trotting horses. American Journal of Veterinary Research 64, 1491–1495.

Kramer, J., Keegan, K.G., Wilson, D.A.J., Smith, B.K., Wilson, D.A.J., 2000. Kinematics of the hind limb in trotting horses after induced lameness of the distal intertarsal and tarsometatarsal joints and intra-articular administration of anesthetic. American Journal of Veterinary Research 61, 1031–1036.

Kramer, J., Keegan, K.G., Kelmer, G., Wilson, D.A., 2004. Objective determination of pelvic movement during hind limb lameness by use of a signal decomposition method and pelvic height differences. American Journal of Veterinary Research 65, 741–747.

Kübber, P., Kastner, J., Girtler, D., Knezevic, P.F., 1994. Erkenntnisse über den einfluß der tiefen palmarnervanästhesie auf das gangbild des lahmheitsfreien pferdes mit hilfe einer kinematischen meßmethode. Pferdeheilkunde 10, 11–21.

Liedtke, A., Moore, S., Witte, T. and Spence, A., 2012. How does loss of digital sensory feedback affect locomotion in the horse? Equine Veterinary Journal 44 (Suppl. 42), 16.

Loomans, J.B.A., Stolk, P.W.T., van Weeren, P.R., Vaarkamp, H., Barneveld, A., 2007. A survey of the workload and clinical skills in current equine practices in The Netherlands. Equine Veterinary Education 19, 162–168.

Maliye, S., Voute, L., Lund, D., Marshall, J.F., 2013. An inertial sensor-based system can objectively assess diagnostic anaesthesia of the equine foot. Equine Veterinary Journal 45, 26–30.

Maliye, S., Voute, L.C., Marshall, J.F., 2015. Naturally-occurring forelimb lameness in the horse results in significant compensatory load redistribution during trotting. The Veterinary Journal 204, 208–213.

Maliye, S., Marshall, J.F., 2016. Objective assessment of the compensatory effect of clinical hind limb lameness in horses: 37 cases (2011–2014). Journal of the American Veterinary Medical Association 249, 940–944.

Marshall, J.F., Lund, D.G., Voute, L.C., 2012. Use of a wireless, inertial sensor-based system to objectively evaluate flexion tests in the horse. Equine Veterinary Journal 44, 8–11.

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, 652–656.

Merkens, H.W., Schamhardt, H.C., 1988a. Evaluation of equine locomotion during different degrees of experimentally induced lameness. II: Distribution of ground reaction force patterns of the concurrently loaded limbs. Equine Veterinary Journal 20 (Suppl. 6), 107–112.

Merkens, H.W., Schamhardt, H.C., 1988b. Evaluation of equine locomotion during different degrees of experimentally induced lameness. I: Lameness model and quantification of ground reaction force patterns of the limbs. Equine Veterinary Journal 20 (Suppl. 6), 99–106.

Moorman, V.J., Reiser, R.F., Mahaffey, C.A., Peterson, M.L., McIlwraith, C.W., Kawcak, C.E., 2014. Use of an inertial measurement unit to assess the effect of forelimb lameness on three-dimensional hoof orientation in horses at a walk and trot. American Journal of Veterinary Research 75, 800–808.

Morris, E., Seeherman, H., 1987. Redistribution of ground reaction forces in experimentally induced equine carpal lameness. Equine Exercise Physiology 2, 553–563.

Munoz-Nates, F., Chateau, H., Van Hamme, A., Camus, M., Pauchard, M., Ravary-Plumioen, B., Denoix, J.M., Pourcelot, P., Crevier-Denoix, N., 2015. Accelerometric and dynamometric measurements of the impact shock of the equine forelimb and hindlimb at high speed trot on six different tracks - preliminary study in one horse. Computer Methods in Biomechanics and Biomedical Engineering 18 (Suppl. 1), 2012–2013.

Murray, R.C., Dyson, S.J., Tranquille, C., Adams, V., 2006. Association of type of sport and performance level with anatomical site of orthopaedic injury diagnosis. Equine Veterinary Journal 38 (Suppl. 36), 411–416.

Nielsen, T.D., Dean, R.S., Robinson, N.J., Massey, A., Brennan, M.L., 2014. Survey of the UK veterinary profession: common species and conditions nominated by veterinarians in practice. Veterinary Record 174, 324.

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, 347–351.

Oosterlinck, M., Pille, F., Sonneveld, D.C., Oomen, A.M., Gasthuys, F., Back, W., 2012. Contribution of dynamic calibration to the measurement accuracy of a pressure plate system throughout the stance phase in sound horses. The Veterinary Journal 193, 471–474.

Parkes, R.S. V, 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, 112–117.

Peham, C., Scheidl, M., Licka, T., 1996. A method of signal processing in motion analysis of the trotting horse. Journal of Biomechanics 29, 1111–1114.

Peham, C., 2013. Signals from materials. In: Back, W., Clayton, H.M. (Eds.), Equine Locomotion, Second Edn. Saunders Elsevier, St. Luis, MO, USA, pp. 61–71.

Peloso, J.G., Stick, J.A., Soutas-Little, R.W., Caron, J.C., DeCamp, C.E., Leach, D.H., 1993. Computer-assisted three-dimensional gait analysis of amphotericin-induced carpal lameness in horses. American Journal of Veterinary Research 54, 1535–1543.

Persson Sjödin, E., Serra Braganca, F.M., Pfau, T., Egenvall, A., Weishaupt, M.A., Rhodin, M., 2016. Movement symmetry of the withers can be used to discriminate primary forelimb lameness from compensatory forelimb asymmetry in horses with induced lameness. Equine Veterinary Journal 48, 32–33.

Pfau, T., Witte, T.H., Wilson, A.M., 2005. A method for deriving displacement data during cyclical movement using an inertial sensor. The Journal of Experimental Biology 208, 2503–2514.

Pfau, T., Stubbs, N.C., Kaiser, L.J., Brown, L.E.A., Clayton, H.M., 2012a. Effect of trotting speed and circle radius on movement symmetry in horses during lunging on a soft surface. American Journal of Veterinary Research 73, 1890–1899.

Pfau, T., Jennings, C., Mitchell, H., Olsen, E., Walker, A., Egenvall, A., Tröster, S., Weller, R., Rhodin, M., 2014. Lungeing on hard and soft surfaces: Movement symmetry of trotting horses considered sound by their owners. Equine Veterinary Journal 48, 83-89.

Pourcelot, P., Audigié, F., Degueurce, C., Denoix, J.M., Geiger, D., n.d. Kinematic symmetry index: a method for quantifying the horse locomotion symmetry using kinematic data. Veterinary Research 28, 525–538.

Ratzlaff, M.H., Grant, B.D., Adrian, M., 1982. Quantitative evaluation of equine carpal lamenesses. Journal of Equine Veterinary Science 2, 78–88.

Rhodin, M., Pfau, T., Roepstorff, L., Egenvall, A., 2013. Effect of lungeing on head and pelvic movement asymmetry in horses with induced lameness. The Veterinary Journal 198, e39–e45.

Rhodin, M., Roepstorff, L., French, A., Keegan, K.G., Pfau, T., Egenvall, A., 2015. Head and pelvic movement asymmetry during lungeing in horses with symmetrical movement on the straight. Equine Veterinary Journal 48, 315–320.

Rhodin, M., Egenvall, A., Haubro Andersen, P., Pfau, T., Pfau, T., Weeren, P., 2017. Head and pelvic movement asymmetries at trot in riding horses in training and perceived as free from lameness by the owner. PLoS One 12, e0176253.

Roepstorff, L., Drevemo, S., 1993. Concept of a force-measuring horseshoe. Acta Anatomica 146, 114–119.

Ross, M.W., 2013. Movement. In: Ross, M.W., Dyson, S. (Eds.), Diagnosis and Management of Lameness in the Horse, Second Edn. Saunders Elsevier, St. Louis, MO, USA, pp. 71–72.

Schumacher, J., Schramme, M.C., Moyer, W., 2014. Review of mistakes that can be made when interpreting the results of diagnostic analgesia during a lameness examination. Proceedings of the AAEP Annual Convention, Salt Lake City, Utah, 6-10 December 2014, Vol. 60. pp. 83–94.

Serra Braganca, F.M., Mancini, I., Brommer, H., Malda, J., Visser, J., van Weeren, P.R., 2016. Compensatory mechanism of gait adaptation to bilateral stifle joint injuries in shetland ponies at trot. Equine Veterinary Journal 48, 17–17.

Sinclair, J., Taylor, P.J., Hobbs, S.J., 2013. Digital filtering of three-dimensional lower extremity kinematics: an assessment. Journal of Human Kinetics 39, 25–36.

Starke, S.D., Willems, E., May, S. a., Pfau, T., 2012a. Vertical head and trunk movement adaptations of sound horses trotting in a circle on a hard surface. The Veterinary Journal 193, 73–80.

Starke, S.D., Witte, T.H., May, S. a, Pfau, T., 2012b. Accuracy and precision of hind limb foot contact timings of horses determined using a pelvis-mounted inertial measurement unit. Journal of Biomechanics 45, 1522–1528.

Starke, S.D., Willems, E., Head, M., May, S.A., Pfau, T., 2012c. Proximal hindlimb flexion in the horse: Effect on movement symmetry and implications for defining soundness. Equine Veterinary Journal 44, 657–663.

Starke, S.D., Raistrick, K.J., May, S. a., Pfau, T., 2013. The effect of trotting speed on the evaluation of subtle lameness in horses. The Veterinary Journal 197, 245–252.

Thomsen, M.H., Persson, A.B., Jensen, A.T., Sørensen, 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 (Suppl. 38), 510–515.

Tóth, F., Schumacher, J., Schramme, M.C., Hecht, S., 2014. Effect of anesthetizing individual compartments of the stifle joint in horses with experimentally induced stifle joint lameness. American Journal of Veterinary Research 75, 19–25.

Uhlir, C., Licka, T., Kübber, P., Peham, C., Scheidl, M., Girtler, D., 1997. Compensatory movements of horses with a stance phase lameness. Equine Veterinary Journal 29 (Suppl. 23), 102–105.

Van de Water, E., Oosterlinck, M., Pille, F., 2016. The effect of perineural anaesthesia and handler position on limb loading and hoof balance of the vertical ground reaction force in sound horses. Equine Veterinary Journal 48, 608–612.

van den Bogert, A.J., Weeren, P.R. van, Schamhardt, H.C., 1990. Correction for skin displacement errors in movement analysis of the horse. Journal of Biomechanics 23, 97–101.

van Heel, M.C. V, Barneveld, A., van Weeren, P.R., Back, W., 2004. Dynamic pressure measurements for the detailed study of hoof balance: the effect of trimming. Equine Veterinary Journal 36, 778–782.

van Loon, J.P. a M., de Grauw, J.C., van Dierendonck, M., L'ami, J.J., Back, W., van Weeren, P.R., 2010. Intra-articular opioid analgesia is effective in reducing pain and inflammation in an equine LPS induced synovitis model. Equine Veterinary Journal 42, 412–419.

van Weeren, P.R., van den Bogert, A.J., Barneveld, A., 1988. Quantification of skin displacement near the carpal, tarsal and fetlock joints of the walking horse. Equine Veterinary Journal 20, 203–208.

van Weeren, P.R., van den Bogert, A.J., Barneveld, A., 1990a. Quantification of skin displacement in the proximal parts of the limbs of the walking horse. Equine Veterinary Journal 22 (Suppl. 9), 110–118.

van Weeren, P.R., van den Bogert, A.J., Barneveld, A., Hartman, W., Kersjes, A.W., 1990b. The role of the reciprocal apparatus in the hind limb of the horse investigated by a modified CODA-3 opto-electronic kinematic analysis system. Equine Veterinary Journal 22 (Suppl. 9), 95–100.

van Weeren, P.R., 2013. History, in: Clayton, H.M., Back, W. (Eds.), Equine Locomotion, Second Edn. Saunders Elsevier, St. Luis, MO, USA, pp. 1–30.

van Weeren, P.R., Pfau, T., Rhodin, M., Roepstorff, L., Serra Bragança, F.M., Weishaupt, M.A., 2017. Do we have to redefine lameness in the era of quantitative gait analysis? Equine Veterinary Journal 49, 567-569.

Weishaupt, M.A., Hogg, H.P., Wiestner, T., Denoth, J., Stüssi, E., Auer, J. A., 2002. Instrumented treadmill for measuring vertical ground reaction forces in horses. American Journal of Veterinary Research 63, 520–527.

Weishaupt, M. A., Wiestner, T., Hogg, H.P., Jordan, P., Auer, J.A., 2006. Compensatory load redistribution of horses with induced weight-bearing forelimb lameness trotting on a treadmill. The Veterinary Journal 171, 135–146.

Weishaupt, M.A., 2008. Adaptation strategies of horses with lameness. Veterinary Clinics of North America: Equine Practice 24, 79–100.

Weishaupt, M.A., Hogg, H.P., Auer, J.A., Wiestner, T., 2010a. Velocity-dependent changes of time, force and spatial parameters in Warmblood horses walking and trotting on a treadmill. Equine Veterinary Journal 42, 530–537.

Weishaupt, M.A., Wiestner, T., Hogg, H.P., Jordan, P., Auer, J.A., 2010b. Compensatory load redistribution of horses with induced weightbearing hindlimb lameness trotting on a treadmill. Equine Veterinary Journal 36, 727–733.

Wennerstrand, J., Gómez Álvarez, C.B., Meulenbelt, R., Johnston, C., van Weeren, P.R., Roethlisberger-Holm, K., Drevemo, S., 2009. Spinal kinematics in horses with induced back pain. Veterinary and Comparative Orthopaedics and Traumatology 22, 448–454.

Wyn-Jones, G., 1988. The diagnosis of the causes of lameness. In: Equine Lameness, Blackwell Scientific Publications, Oxford, p. 5.

Table 1

Summary of publications describing kinetic changes due to lameness.

Parameter	Measuring tool	Treadmill / overground	Model	Response measured on the lame limb	Reference
Peak vertical force	Force plate	Overground	Induced lameness, modified shoe	Decreases	(Merkens and Schamhardt, 1988a; Ishihara et al., 2005)
			Induced lameness, carpal joint defect.	Decreases	(Morris and Seeherman, 1987)
			Induced lameness, flexor tendon lesion	Decreases	(Keg et al., 1994) (Clayton et al., 2000)
			Induced lameness, LPS injection (distal intertarsal and tarsometatarsal joints)	Decreases	(Khumsap et al., 2003)
		Treadmill	Induced lameness modified shoe	Decreases	(Weishaupt et al., 2006, 2010b)
Vertical Impulse	Force plate	Overground	Induced lameness modified shoe	Decreases	(Merkens and Schamhardt, 1988a; Ishihara et al., 2005)
			Induced lameness, carpal joint defect	Decreases	(Morris and Seeherman, 1987)
			Induced lameness, flexor tendon lesion	Decreases	(Keg et al., 1994)
		Treadmill	Induced lameness modified shoe	Decreases	(Weishaupt et al., 2006, 2010b)
Breaking force impulse	Force plate	Overground	Induced lameness, LPS injection	Decreases (in the highest degrees of lameness)	(Ishihara et al., 2005)
			Induced lameness, flexor tendon lesion	Decreases	(Keg et al., 1994; Clayton et al., 2000)
			Induced lameness, carpal joint defect	Decreases	(Morris and Seeherman, 1987)
Breaking force peak	Force plate	Overground	Induced lameness, LPS injection	Decreases	(Ishihara et al., 2005)
			Induced lameness, carpal joint defect	Decreases	(Morris and Seeherman, 1987)
			Induced lameness, flexor tendon lesion	Decreases	(Clayton et al., 2000)
Propulsive force peak	Force plate	Overground	Induced lameness, LPS injection	Decreases (in the highest degrees of lameness)	(Ishihara et al., 2005)
			Induced lameness, flexor tendon lesion	Decreases	(Keg et al., 1994)
			Induced lameness, carpal joint defect	Not significantly affected	(Morris and Seeherman, 1987)
			Induced lameness, flexor tendon lesion	Not significantly affected	(Clayton et al., 2000)
Propulsive force impulse	Force plate	Overground	Induced lameness, LPS injection	Decreases (in the highest degrees of lameness)	(Ishihara et al., 2005)
			Induced lameness, flexor tendon lesion	Not significantly affected	(Keg et al., 1994; Clayton et al., 2000)
			Induced lameness, carpal joint defect	Not significantly affected	(Morris and Seeherman, 1987)
Time of zero-crossing of horizontal ground reaction force as a percentage of stance time	Force plate	Overground	Induced lameness, flexor tendon lesion	Reduced	(Keg et al., 1994)
			Induced lameness, LPS injection	Decreases (in the highest degrees of lameness)	(Ishihara et al., 2005)
Stance duration	Force plate	Overground	Induced lameness, LPS injection	Increases	(Ishihara et al., 2005)
			Induced lameness, carpal joint defect	Not significantly affected	(Morris and Seeherman, 1987)
			Induced lameness, flexor tendon lesion	Not significantly affected	(Clayton et al., 2000)
		Treadmill	Induced lameness, modified shoe	Increases	(Weishaupt et al., 2006, 2010b)
Swing duration	Force plate	Treadmill	Induced lameness modified shoe	Decreases	(Weishaupt et al., 2006, 2010b)
Stride frequency	Force plate	Treadmill	Induced lameness modified shoe	Increases	(Weishaupt et al., 2006, 2010b)

LPS: lipopolysaccharide.

Table 2

Summary of publications describing kinematic changes due to lameness.

Parameter	Detailed parameter	Measured	Treadmill /overground	Model	Response measured on the specific kinematic parameter	Reference
Head vertical displacement	MinDiff	OMC	Treadmill	Induced FL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Keegan et al., 2001, 2000; Kelmer et al., 2005)
		IMU	Overground	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Rhodin et al., 2013)
	MaxDiff	OMC	Treadmill	Induced FL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Kelmer et al., 2005)
		IMU	Overground	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Rhodin et al., 2013)
	Range up	OMC	Treadmill	Induced FL lameness – modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Peloso et al., 1993; Buchner et al., 1996a)
	SI_{up}	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases	(Buchner et al., 1996a)
				Induced HL lameness – modified shoe	Decreases – only in higher degree of lameness	(Buchner et al., 1996a)
	Head signal transformation (FFT)	OMC	Treadmill	Induced FL lameness - modified shoe	Increased signal amplitude of fundamental wave after FFT transformation.	(Peham et al., 1996)
Head acceleration	Maximum head acceleration	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases during the lame stance and increases during the contralateral stance.	(Buchner et al., 1996a)
	Head acceleration amplitude	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases during the lame stance and increases during the contralateral stance.	(Buchner et al., 1996a)
Withers vertical displacement	Range up	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases	(Peloso et al., 1993; Buchner et al., 1996a)
	SI_{up}	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases – only in higher degree of lameness	(Buchner et al., 1996a)
	MinDiff	OMC	Overground	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Persson Sjödin et al., 2016)
Withers acceleration	Withers maximum acceleration	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases during the lame stance	(Buchner et al., 1996a)
Pelvis vertical displacement	MinDiff	Tri-axis accelerometer	Overground	Induced stifle synovitis (intra articular injection of IL-1β)	Increases. Values will be < or > than zero depending on the side of lameness	(Tóth et al., 2014)
		OMC	Treadmill	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Kramer et al., 2004; Kelmer et al., 2005)
		OMC	Treadmill	Induced HL lameness – LPS injection hock	Not significantly affected	(Kramer et al., 2000)
		IMU	Overground	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Rhodin et al., 2013)
	MaxDiff	Tri-axis accelerometer	Overground	Induced stifle synovitis (intra-articular injection of IL-1β)	Increases. Values will be < or > than zero depending on the side of lameness	(Tóth et al., 2014)
		OMC	Treadmill	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Kramer et al., 2004; Kelmer et al., 2005)
		IMU	Overground	Induced FL/HL lameness - modified shoe	Increases. Values will be < or > than zero depending on the side of lameness	(Rhodin et al., 2013)
	Pelvis vertical displacement FFT, signal to noise ratio.	OMC	Treadmill	Induced HL lameness - modified shoe	Increased signal to noise FFT ratio	(Kramer et al., 2004)
	Range Up	OMC	Treadmill	Induced HL lameness – modified shoe	Decreases	(Buchner et al., 1996a)
	Tuber coxae upward movement amplitude during stance of the lame limb.	OMC	Treadmill	Induced HL lameness – modified shoe	Decreases	(Buchner et al., 1996a)
	SI_{up}	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases	(Buchner et al., 1996a)
				Induced HL lameness – modified shoe	Decreases	(Buchner et al., 1996a)
Pelvis acceleration	Sacrum Acceleration amplitude	OMC	Treadmill	Induced HL lameness – modified shoe	Decreased maximum acceleration and acceleration amplitude during lame stance	(Buchner et al., 1996a)
Trunk	Acceleration symmetry	Tri-axis accelerometer	Treadmill & overground	Induced FL lameness - modified shoe	Decreased coefficient of correlation of the dorsoventral acceleration signal autocorrelation.	(Barrey et al., 1994)
		Tri-axis accelerometer	Overground	Induced FL lameness – saline injection in to metacarpophalangeal joint	A-score[a] increases. Values will be < or > than zero depending on the side of lameness; S-score[b] increases.	(Thomsen et al., 2010)
Back	Back range of motion	OMC	Treadmill	Induced lameness – modified shoe	Flexion-extension and lateral bending of back segments change significantly both in walk and trot.	(Gómez Álvarez et al., 2007, 2008)
				Induced back pain – Lactic acid injection	Flexion-extension and lateral bending of back segments change significantly both in walk and trot	(Wennerstrand et al., 2009)
	Pelvic axial rotation	OMC	Treadmill	Induced lameness – modified shoe	Walk – Increased; Trot - Decreased	(Gómez Álvarez et al., 2007, 2008)
				Induced back pain	Not significantly affected	(Wennerstrand et al., 2009)

OMC: Optical motion capture; IMU: Inertial measurement unit; LPS: lipopolysaccharide; FL: Forelimb; HL: Hind limb; MinDiff: Difference in minimum position between two consecutive steps; MaxDiff: Difference in maximum position between two consecutive steps; Range up/down: Difference in range of motion in the upwards/downwards direction between two consecutive steps; $SI_{Up/Down}$: Symmetry index (between -1 and 1) in range of motion in the upwards/downwards direction between two consecutive steps. FFT: Fast Fourier transform. [a]The natural logarithmic quotient of the total upwards accelerations during stance of the right and the left diagonals. [b]The natural logarithmic quotient of the squared odd-numbered and even-numbered Fourier coefficients from the dorsoventral acceleration signal.

Table 3

Summary of publications describing limb kinematic changes due to lameness.

Parameter studied	Detailed parameter	Measured	Treadmill / overground	Model	Response measured on the specific kinematic parameter	Reference
Limbs	Stance duration	OMC	Treadmill	Induced FL lameness – modified shoe	Increased on the sound forelimb and decreased on the diagonal hind limb	(Buchner et al., 2010)
				Induced HL lameness – modified shoe	Decreased only on the ipsilateral and diagonal forelimb	(Buchner et al., 2010)
	Stride duration	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases	(Keegan et al., 2000; Buchner et al., 2010)
				Induced HL lameness – modified shoe	Decreases	(Buchner et al., 2010)
		Force plate	Treadmill	Induced FL lameness – modified shoe	Decreases	(Weishaupt et al., 2006)
	Relative stance duration as a percentage of the stride duration	OMC	Treadmill	Induced FL lameness – modified shoe	Increases	(Keegan et al., 2000; Buchner et al., 2010)
				Induced HL lameness – modified shoe	Not significantly affected	(Buchner et al., 2010)
		Force plate	Treadmill	Induced FL lameness – modified shoe	Increases	(Weishaupt et al., 2006)
				Induced HL lameness – modified shoe	Increases	(Weishaupt et al., 2006)
	Diagonal advanced placement	OMC	Treadmill	Induced FL lameness – modified shoe	Decreases – lame diagonal	(Buchner et al., 2010)
				Induced HL lameness – modified shoe	Not significantly affected	(Buchner et al., 2010)
	Limb joint angles	OMC	Treadmill	Induced lameness – modified shoe	Various significant responses depending on the measured joint ROM	(Buchner et al., 1996b; Keegan et al., 2000)
				Induced lameness – intra-articular LPS injection	Various significant responses depending on the measured joint ROM	(Kramer et al., 2000; van Loon et al., 2010)
			Overground	Induced lameness, flexor tendon lesion	Various significant responses depending on the measured joint ROM	(Clayton et al., 2000)
			Overground	Induced lameness, LPS injection (distal intertarsal and tarsometatarsal joints)	Reduction of ROM of the tarsal joint	(Khumsap et al., 2003)
		Goniometry	Overground	Clinical lameness (carpal)	Reduced ROM of the affected joint, in unilateral carpal lameness. No effect in bilateral lameness.	(Ratzlaff et al., 1982)
	Protraction (max)	OMC	Treadmill	Induced lameness – modified shoe	Decreases (only for the forelimbs, walk and trot)	(Buchner et al., 1996b)
					Not significantly affected	(Gómez Álvarez et al., 2007, 2008)
					Increased – protraction distance	(Keegan et al., 2000)
				Induced HL lameness – tarsal joint LPS injection	Increased protraction length	(Kramer et al., 2000)
			Overground	Induced lameness, flexor tendon lesion	Reduced, compared to the contralateral limb	(Clayton et al., 2000)
	Retraction (max)	OMC	Treadmill	Induced lameness – modified shoe	Decreases (only for the hind limbs, walk and trot)	(Buchner et al., 1996b)
					Not significantly affected	(Gómez Álvarez et al., 2007, 2008)
				Induced HL lameness – tarsal joint LPS injection	Not significantly affected	(Kramer et al., 2000)
			Overground	Induced lameness, flexor tendon lesion	Increased compared to the contralateral limb	(Clayton et al., 2000)
	Step length	OMC	Treadmill	Induced lameness – modified shoe	Decreases (only for the hind limbs at trot)	(Buchner et al., 1996b)
	Hoof orientation angles	Hoof mounted IMU sensors	Overground	Induced lameness	Various significant responses based on measured angle orientation.	(Moorman et al., 2014)
	Max hoof height	OMC	Treadmill	Induced lameness – modified shoe	Decreases (only for hind limbs at trot)	(Buchner et al., 1996b)
	Fetlock extension	OMC	Treadmill	Induced lameness – modified shoe	Decreases	(Buchner et al., 1996b; Clayton et al., 2000; Keegan et al., 2000)

OMC: Optical motion capture; IMU: Inertial measurement unit; LPS: lipopolysaccharide; FL: Forelimb; HL: Hind limb; FFT: Fast Fourier transform. ROM: Range of motion.

Figure legends

Fig. 1. Graphical presentation of the vertical displacement of the pelvis during a complete stride at the trot (top) and vertical/horizontal ground reaction forces (bottom). The stance phase of each limb is represented by the horizontal bars below. The graph illustrates a left hind lameness. The vertical displacement of the pelvis, the vertical ground reaction force and the horizontal ground reaction force are presented in blue, green and black, respectively. Symmetry of the upward vertical displacement (SI_{up}) is calculated as the difference between Range up 1 and Range up 2, and the symmetry of the downward vertical displacement (SI_{down}) is calculated as the difference between Range down 1 and Range down 2 (LH: Left hind, RH: Right hind, LF: Left front, RF: Right front, PVF: Peak vertical force, PBF: Peak breaking force, PPF: Peak propulsive force, SD: Stance Duration, asterisk: approximate timing of hoof-on).

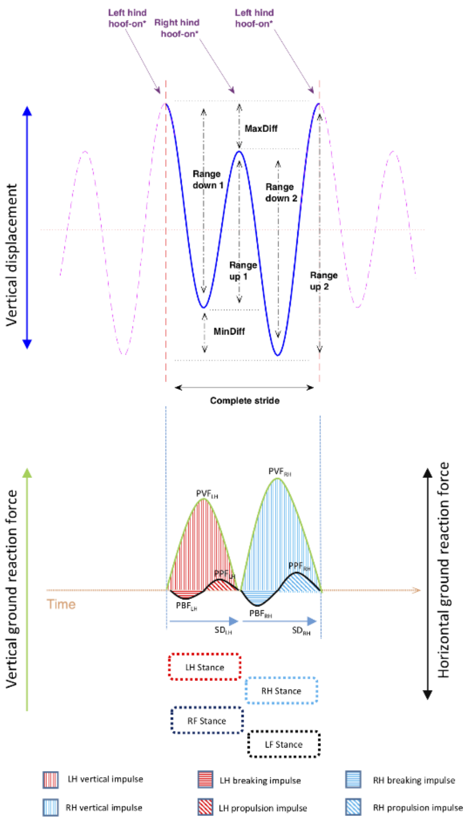


Fig. 2. Schematic representation of the compensatory movements (yellow) of the head and pelvis, as traditionally observed during subjective lameness assessment (I, II) in case of a primary (red) forelimb limb lameness (I: with a compensatory contralateral (diagonal) vertical displacement asymmetry of the pelvis, indicated as a) and in case of a primary hind limb lameness (II: with an ipsilateral compensatory vertical displacement asymmetry of the head, indicated as b). In objective gait assessment (III, IV), a primary forelimb lameness (III) is commonly seen accompanied by a compensatory effect on the contralateral pelvis MaxDiff (d) and the ipsilateral pelvis MinDiff (c). For a primary hind limb lameness (IV), effects on sagittal head MinDiff and MaxDiff (e) have been described. See Table 1 and Fig. 1 for a description of these parameters.

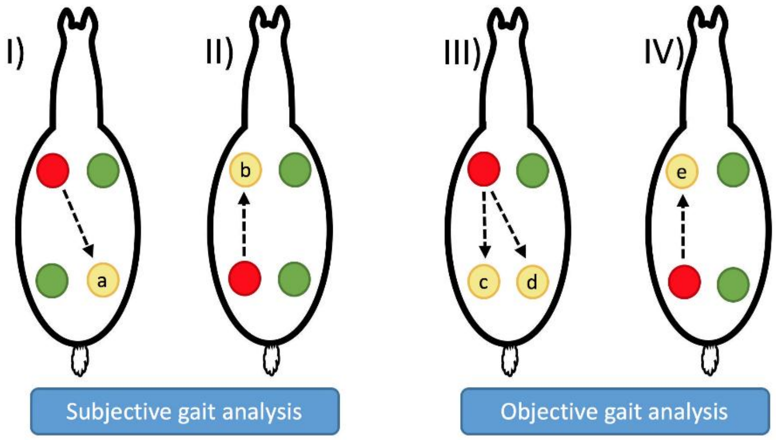
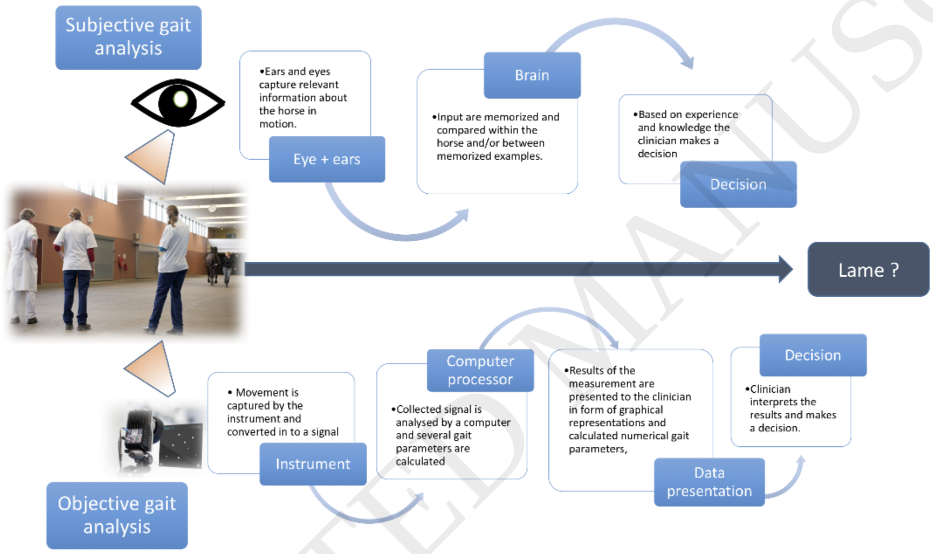


Fig. 3. The parallel decision-making process in a lameness work-up supported by the use of objective gait analysis.



- Ears and eyes capture relevant information about the horse in motion.
- Input are memorized and compared within the horse and/or between memorized examples.
- Based on experience and knowledge the clinician makes a decision
- Movement is captured by the instrument and converted in to a signal
- Collected signal is analysed by a computer and several gait parameters are calculated
- Results of the measurement are presented to the clinician in form of graphical representations and calculated numerical gait parameters,
- Clinician interprets the results and makes a decision.