



# Methods, Applications and Limitations of Gait Analysis in Horses

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## SUMMARY

Over the last 30 years, the increase in interest in horses for racing and riding activities has stimulated scientific research in equine locomotion. This paper presents a review of the measurement methods and their applications used to assess equine locomotion. After describing gaits and velocity-related changes in stride variables, the current applications of gait analysis are presented. The economic consequences of lameness justifies the great effort now being put into lameness quantification and prevention. To improve breeding and reduce the costs of training, early performance evaluation tests for each discipline are proposed. After extensive fundamental and methodological research on the various aspects of equine locomotion, the horse industry should benefit from the applications of gait analysis by improving the profitability of racing and riding activities.

**KEYWORDS:** Horse; locomotion; biomechanics; performance; lameness.

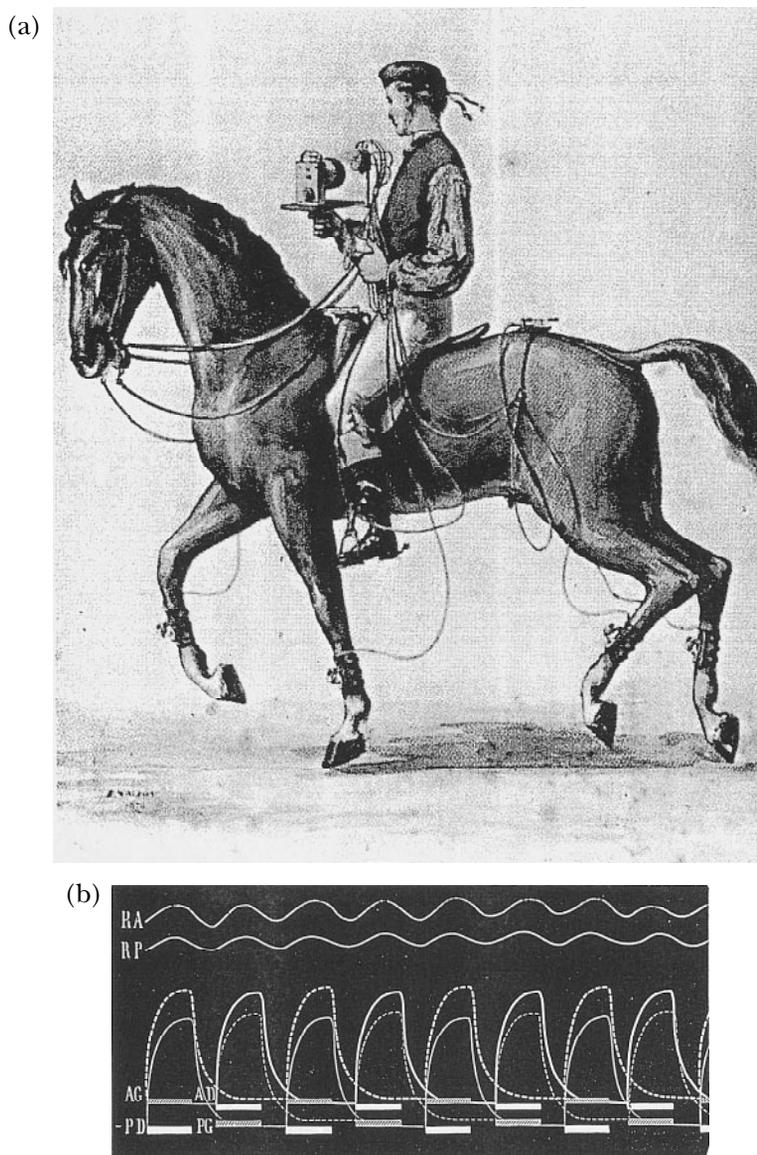
## INTRODUCTION

According to recent archeological research in the Ukraine, horses have been domesticated and ridden since about 4000 BC. From this date, humans began to understand and exploit the locomotor processes of the horse in order to optimize the use of this animal power for hunting, transporting a rider or pulling a load. Many images of ridden and harnessed horses have been found in Middle-Eastern civilizations, but the first treatise '*Hippike*' dealing with the body conformation of the horse and riding techniques was written by Xenophon (445–354 years BC). Aristotle (384–322 BC) described the anatomy of the equine locomotor apparatus in more detail. In the XVIth and XVIIth Century, the development of several riding schools in Italy, Spain, Portugal, France, and Austria increased knowledge about horse conformation, and there was interest in using its locomotion for academic riding schools and military functions. The first scientific approach was undertaken in the

XVIIth and XVIIIth Century by veterinarians such as Bourgelat (1754). In the XIXth Century, the first experimental measurements were undertaken by Marey (1873, 1894), who studied the timing of each gait using a chronographic method (Fig. 1), and then by Muybridge (1887), who used a series of cameras to analyse the horse's locomotion. During the same period, the riding master's Baucher, and General Morris, cited by Lenoble du Teil (1893), undertook the measurement of the weight-bearing distribution between the forelimbs and hindlimbs. The use of animal power declined at the beginning of the XXth Century with the development of machines but, over the last 30 years, the increasing interest in horses for racing and riding activities has stimulated scientific research in equine biomechanics.

From a biological point of view, locomotion can be defined as the ultimate mechanical expression of exercise activity. In order to sustain an exercise activity, the organism requires a synergy between several systems that are functionally linked and regulated by the nervous system. The cardiovascular and respiratory systems provide nutrients and oxygen to muscle which then transforms biochemical energy into mechanical work during muscle con-

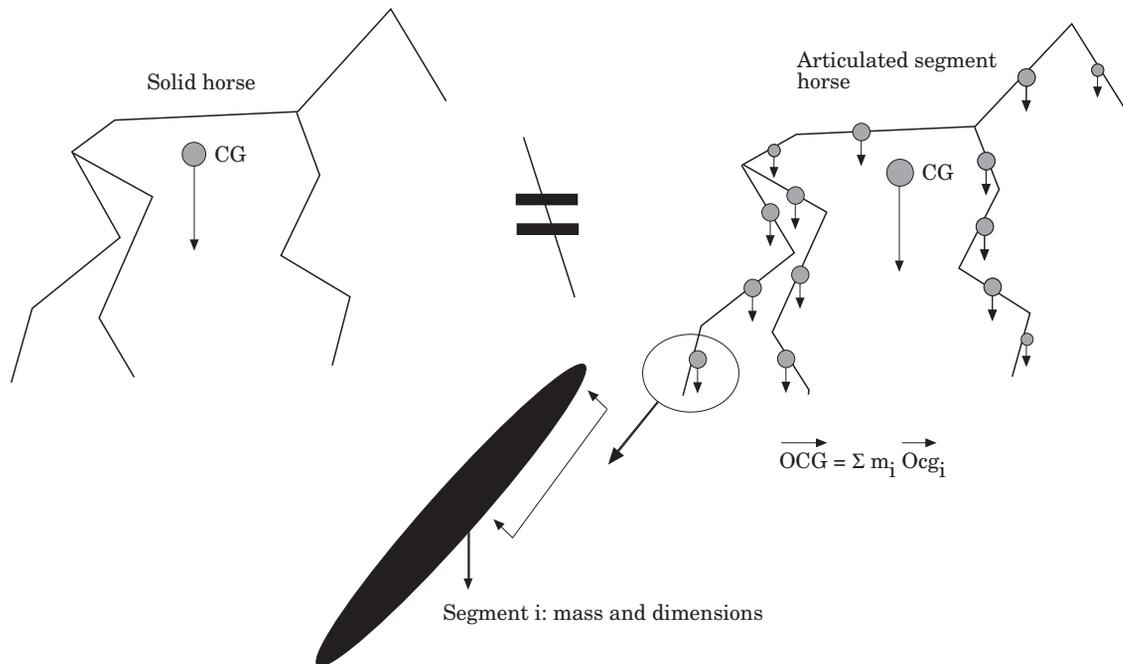
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**Fig. 1.** (a) Horse equipped with pneumatic accelerometers attached to the limbs, saddle and tuber sacrale for measuring temporal gait parameters (Reproduced with kind permission from Marey, 1873; E. Valton, '*Méthode graphique, cheval au trot, cylindre enregistreur posté par le cavalier...*', watercolour on paper 1872). (b) Time-related changes in the pressure obtained from the pneumatic accelerometers at trot (RA=Saddle; RP-Tuber sacrale; AG=Left forelimb; AD=Right forelimb; PD=Right hindlimb; PG=Left hindlimb).

traction. The complex organization of the locomotor apparatus under neurosensorial control makes it possible to use all the individual muscle contractions for moving the limbs to support and propel the body. Biochemically, locomotion involves moving all the body and limb segments in rhythmic and automatic patterns which define the various gaits. As with any other body system, a horse's movement can be explained by mechanical laws.

The athletic horse often suffers from injuries of its locomotor apparatus because of human management errors (nutrition, training, shoeing, breeding), bad environmental conditions (tracks, weather) and an unfavourable constitution (limb conformation, genetics). In Thoroughbred racehorses, about 53–68% of the wastage is due to lameness (Jeffcott *et al.*, 1982; Rosedale *et al.*, 1985). The extent of this problem justifies the great effort now being put into equine locomotion research,



**Fig. 2.** A horse mechanical model composed of articulated body segments. The location of the general centre of gravity (CG) of the horse can be calculated by considering the mass and the coordinates of the centre of each segment.

including clinical applications and techniques for preventing lameness. Currently, economic factors also favour the development of early performance evaluation in all breeds in order to improve the training and selection of young horses.

This paper presents a review of the measurement methods and their applications used to assess equine locomotion. Current knowledge concerning the velocity-related changes in stride variables in various sporting disciplines and the influence of training will also be discussed. Finally, a survey of the practical applications of equine gait analysis will be presented. Other reviews on equine gait analysis have been published previously (Leach & Dagg, 1983a,b; Leach and Crawford, 1983; Leach, 1983; Dalin & Jeffcott, 1985; Leach, 1987), but the present review summarizes the new methods and results obtained during the last 10 years.

## METHODS FOR MEASURING LOCOMOTOR VARIABLES

### *Mechanical laws as applied to the body*

A simple model of the horse skeleton can be defined as a set of segments articulated one to another. Consequently, the body of the horse as any other animal or human, follows exactly the same

mechanical laws as a series of inanimate objects (Fig. 2). However, these laws need to be applied carefully, because the mechanical equations that determine the motions of a set of articulated body segments are much more complicated than those that determine the motion of a rigid body system like a bullet. This great difference is often the cause of theoretical errors. Because living organisms follow Newtonian mechanics, there are two complementary approaches to studying the body in motion:

- **Kinetics or dynamics** is the study of cause of the motion, which can be explained by the force applied to the body, its mass distribution and its dimensions. Kinetics is concerned with forces, accelerations, energy, and work which are also in relation to kinematic variables such as acceleration and velocity.
- **Kinematics** is the study of changes in the position of the body segments in space during a specified time. The motions are described quantitatively by linear and angular variables that relate time, displacement, velocity and acceleration. No reference is made in kinematics to the cause of motion.

### *Kinetic or dynamic analysis*

Marey (1873) was the first to use a pressure sensor attached to the shoe under the hoof and accelerometers attached to the limbs to measure the hoof-ground contact durations at the various gaits. More recently, modern sensor technology has been used to make accurate measurements over a large range of conditions. However, the measurement principles have remained identical. The external forces are measured using electronic force sensors that record the ground reaction forces when the hooves are in contact with the ground. The sensors can be installed either on the ground in a force plate or in a force shoe device, attached under the hoof. The force plates can provide the force amplitude and orientation (vector co-ordinates in three dimensions), the co-ordinates of the point of application of the force and the moment value at this point (Pratt & O'Connor, 1976; Quudus *et al.*, 1978; Ueda *et al.*, 1981; Schamhardt *et al.*, 1991). The accuracy of this type of device is usually good, but the sensitive surface is rather small (about 0.5m<sup>2</sup>) and a visual control of the hoof trajectory is required.

In order to measure ground reaction forces during exercise, several authors have developed hoof force shoes including one or several force sensors (Marey, 1873; Björck, 1958; Frederick & Henderson, 1970; Ratzlaff *et al.*, 1987; Barrey, 1990; Roepstorff & Drevemo, 1993). Depending on their design, these devices can give between one and three components of the ground reaction forces and the point of application. They are generally less accurate than the force plate, and their main disadvantage is the additional weight and thickness of the special shoe. The advantage is that they will measure the ground reaction forces in various types of exercise.

Another indirect ambulatory technique of ground reaction force evaluation was proposed using strain gauges glued onto the hoof wall. After the training of the appropriate artificial neural networks, the ground reaction forces can be estimated from the hoof wall deformations (Savelberg *et al.*, 1997). Strain gauge techniques can be applied to measure *in vivo* the loading of bone or tendon strains in relation to the ground reaction forces. The cortical strains of the metacarpal bone in running Thoroughbreds were measured using this technique in order to understand the effect of loading on the bone structure and building (Davies, 1993, 1994).

Body acceleration measurements are performed using small sensors (accelerometers) that should be firmly attached to the segment under study. This type of sensor measures the instantaneous change of velocity of a body during a given interval which corresponds to the acceleration applied to this body. The acceleration vector is proportional to the resultant force applied to the body where the sensor is attached. The ambulatory measurement provides a convenient way to study the kinetics of a body in various experimental conditions. In order to analyse horse locomotion, the accelerometer should be tightly fixed as near as possible to the body centre of gravity. The caudal part of the sternum between the right and left pectoralis ascendens muscles at the level of the girth provides a good compromise between transducer stability and closeness to the horse's centre of gravity (about 65cm dorsocaudally at the gallop) (Barrey *et al.*, 1994; Barrey & Galloux, 1997). The acceleration signal could be treated by many signal analysis procedures in order to extract the dynamic and temporal stride variables. Calculating the double integral of the linear acceleration makes it possible to estimate the instantaneous linear or angular displacement, such as the saddle motion in space (Galloux *et al.*, 1994). The main advantage of using an accelerometric transducer is the simplicity of the measurement technique both in field or laboratory conditions. The main limitation is that the measurements are given for only one segment with respect to a set of body axes.

### *Kinematic analysis*

A more descriptive approach to locomotion study is to film the animals with one or more cameras in order to analyse the motion characteristics of each body segment. The first kinematic animal locomotion study was undertaken using chronophotography developed by Muybridge (1887) and then improved by Marey (1894). The trajectories of the joints and segments of the body in motion could be measured on the successive images taken at a constant time interval.

The modern approach uses markers glued on the body which are filmed by cinematographic or video cameras. Then, the successive images should be analysed to measure the interesting parameters. Markers are composed of small white spots or half spheres glued onto the skin over standard anatomical locations (Langlois *et al.*, 1978; Leach & Cymbaluck, 1986). They are intended to indicate the approximate instantaneous centre of rotation

of the joint (Leach & Dyson, 1988; Schamhardt *et al.*, 1993). However, the skin displacements over the skeleton during the locomotion generate some artifacts, especially in the proximal joints (van Weeren *et al.*, 1990a,b).

High speed cameras (16mm-500 images/s) have been used to analyse the locomotion of Standard-bred horses, the images being recorded from a camera car under track conditions (Fredricson *et al.*, 1980). The processing of the film for collecting the joint marker coordinates is undertaken manually using a computer. This is a time-consuming task, but many temporospatial stride characteristics can be obtained. With the improvement of the image sensors, many professional high-speed video cameras (100–2000 images/s) and home video cameras (PAL or NTSC Standard: 25–30 images/s or 50–60 frames/s) can be employed for locomotion analysis. The video signal can be treated by a video interface in order to digitize the images, which are then analysed by the appropriate software to collect semi-automatically or automatically the marker co-ordinates in space and time (Drevemo *et al.*, 1993). A more sophisticated motion analysis system uses markers which consists of photodiodes (modified Cartesian Optoelectronic Dynamic Anthropometer CODA-3). The advantage of this system is its good resolution (0.2–2.6mm) in three dimensions, high recording frequency (300Hz) and the automatic tracking possibilities of the active markers (van Weeren *et al.*, 1990c). The main disadvantage is that the subject needs to be equipped with many photodiodes connected to wires.

Most equine locomotion studies show two-dimensional motion analysis, but some systems including four or more video cameras make it possible to reconstruct the motion in three dimensions and to analyse the limb motions on both sides (Peloso *et al.*, 1993; Degeurce *et al.*, 1996). One limit of these sophisticated gait analysis systems is the restricted field view. This is only about 5m, which corresponds to a few walking or trotting strides. In order to analyse sporting exercise in a wider field (up to 30m) under real exercise conditions, a camera panning technique and a parallax correction procedure has been used to study gait variables in dressage and jumping horses (Holmström & Fredricson, 1992; Drevemo & Johnston, 1993; Galloux & Barrey, 1997).

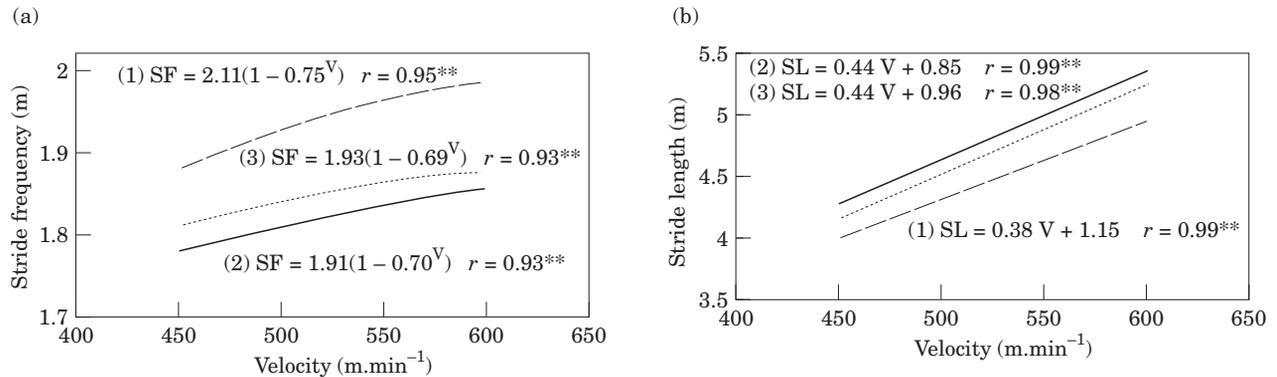
After filming, the operator needs to track manually, semi-automatically or automatically, the co-ordinates of the markers on each image of the

film. In most of the systems, the tracking phase is the limiting factor because of the great number of images to analyse. Manual supervision is required, because the markers are not always easy to detect automatically, especially for distal segments and hidden markers. The use of specific algorithms such as direct linear transform (DLT) is an efficient way to detect automatically the location of the markers on the images.

After collecting the co-ordinates of the markers, the linear and angular velocities can be obtained by computing the first derivative of the trajectories and angles with respect to time. If the filming image frequency is high, the second-order derivative of a trajectory or angular variations with respect to time using appropriate smoothing and filtering techniques provides linear and angular acceleration data. The advantage of kinematics methods is that all the kinematic parameters (displacement, velocity, linear acceleration, angle of rotation, angular velocity and angular acceleration) of the identified segments can be obtained. Several methods have been described to estimate the location of centre of gravity (Springings & Leach, 1986; Kubo *et al.*, 1992) and the moment of inertia of each segment (Galloux & Barrey, 1997). Theoretically, if the centre of gravity and the moment of inertia of each segment can be determined by measuring their mass distribution and their dimensions, it is possible to estimate the kinetic parameters (forces and kinetic moment), which determine the motion of each segment, from the kinematic data. The kinetic energy can be estimated for each segment and for the whole body in motion (Duboy *et al.*, 1994a). From an experimental point of view, the moment and power of the forelimb joints were determined using both kinematic data and ground reaction forces measurements (Colborne *et al.*, 1997a,b).

#### *Conditions of gait measurements*

Under laboratory conditions, it is possible to study the locomotion of horses running on an experimental track or on a treadmill. The latter provides an excellent means of controlling the regularity of the gaits, because the velocity and slope of the treadmill belt are entirely fixed by the operator. In order to analyse the gait of a horse without stress, some pre-experimental exercise sessions are required to accustom it to this unusual exercise condition (Buchner *et al.*, 1994). The horse adapts rapidly at trot, and stride measurements can be undertaken beginning at the third session. For the



**Fig. 3.** Comparison of the velocity relationship in stride variables of horses running overground and on a treadmill. (a) Comparison of the stride frequency: at the same velocity, the stride frequency was lower on a flat or inclined treadmill than on a track. (b) Comparison of the stride length: at the same velocity, the stride length was longer on a treadmill than on a track (Barrey *et al.*, 1993). (---) Track (1); (—) Treadmill 0% (2); (····) Treadmill 3.5% (3). \*\* $P < 0.01$ .

walk, many stride parameters are not stable even after the ninth training session. Within a session, a minimum of 5 min of walking or trotting is required to reach a steady-state locomotion.

Many fundamental locomotion studies have been performed on commercially available high-speed treadmills, since the development of the first installation of this type of machine at the Swedish University of Agricultural Science in Uppsala (Fredricson *et al.*, 1983). At the beginning of human treadmill use, it was suggested that locomotion on a treadmill would be exactly the same as on the ground (van Ingen Schenau, 1980). This hypothesis did not take into account the fact that the human body is not a rigid body system, but an articulated set of segments. In horses, it was demonstrated experimentally that the stride parameters are modified in flat and inclined exercise at trot and canter (Barrey *et al.*, 1993) (Fig. 3). Consequently, the exercise on a flat treadmill generated a lower cardiac and blood lactate response than exercise on the track at the same velocities (Valette *et al.*, 1992; Barrey *et al.*, 1993). The mechanical reasons for these differences are not entirely known today, but some explanations have been suggested by the experimental and theoretical results. The speed of the treadmill belt fluctuates in relationship to the hoof impact on the belt (Savelberg *et al.*, 1994). The total kinetic energy of human runners filmed at the same speed on flat track and treadmill was calculated using the kinematic data (all the body segments being taken into account). It was found that the total kinetic energy was divided by a factor of 10 on the treadmill compared to on the track (Duboy *et al.*, 1994b). This difference was mainly

explained by a reduction of the kinetic energy of each limb and arm segment, which moved with a lower amplitude around the total body centre of gravity on the treadmill as compared to under track conditions. However, these results cannot be extrapolated to the horse, because the measurements and calculations do not relate to quadrupedal locomotion.

At a slow trot, an inclination (6%) of the treadmill tends to increase the stride duration and increases significantly the stance duration of the forelimbs and hindlimbs (Sloet van Oldruitenborgh-Oosterbaan *et al.*, 1997). Kinematic analysis has confirmed that the hindlimbs generated higher propulsion work on the inclined than on the flat treadmill. The inclination of the treadmill did not change the stride length nor did it change the stance, swing and stride duration in a cantering Thoroughbred (Kai *et al.*, 1997).

## GAITS AND LOCOMOTION PATTERNS

### *Gait terminology*

A great diversity exists in equine locomotion patterns because quadrupedal locomotion allows many combinations of inter-limb coordination. Furthermore, horse breeds have been genetically selected and specialized for different uses: draught, riding, meat production, pacing, trotting and galloping races, show jumping, dressage, endurance, etc. A large range of gaits can be observed and classified according to their linear and temporal characteristics: walk, tölt, pace, passage, trot, canter, rotary gallop and transverse gallop (Hildebrand, 1965; Clayton, 1997). This gait variety and complexity has

always created difficulties when it is necessary to choose adequate terminology in order to describe the locomotor phenomenon. Some efforts have been made to define a standard terminology for use in describing equine locomotion (Leach *et al.*, 1984; Clayton, 1989; Leach, 1993).

The following few terms are defined for clarity of this paper. A **gait** can be defined as a complex and strictly co-ordinated rhythmic and automatic movement of the limbs and the entire body of the animal which result in the production of progressive movements. Two types of gait can be distinguished by the symmetry or asymmetry of the limb movement sequence with respect to time and the median plane of the horse: **symmetric gaits** (walk, tölt, pace, trot) and **asymmetric gaits** (canter, gallop). Within each gait there exist continuous variations. Among the normal variations of the trot, the speed of the gait increases from collected to extended trot. Passage and piaffe are two dressage exercises derived from the collected trot. In racing trotters, abnormal trot irregularities can occur during a race: at the aubin, the forelimbs gallop and the hindlimbs trot; while at the traquenard, the forelimbs trot and the hindlimbs gallop. The **stride** is defined as a full cycle of limb motion. Since the pattern is repeated, the beginning of the stride can be at any point in the pattern and the end of that stride at the same place in the beginning of the next pattern. A complete limb cycle includes a **stance phase** when the limb is in contact with the ground and **swing phase** when the limb is not in contact with the ground. During the **suspension phase** at trot, pace, canter or gallop, there is no hoof contact with the ground. The duration of the stride is equal to the sum of the stance and swing phase durations. The **stride frequency** corresponds to the number of strides performed per unit of time. The stride frequency is equal to the inverse of stride duration and is usually expressed in stride/s or in hertz (Hz). The **stride length** corresponds to the distance between two successive hoof placements of the same limb.

#### *Velocity-related changes in stride characteristics*

To increase velocity, the horse can switch gait from walk to trot and from trot to canter and then extend the canter to gallop. Each gait can be also extended by changing the spatial and temporal characteristics of its strides. It appears that each horse has a preferred speed for the trot to gallop transition and this particular speed is related to an optimal metabolic cost of running (Hoyt & Taylor, 1981).

However, another experiment has demonstrated that the trot–gallop transition is triggered when the peak of ground reaction force reaches a critical level of about 1 to 1.25 times the body weight (Farley & Taylor, 1991). Carrying additional weight reduces the speed of trot–gallop transition.

For increasing the speed at a particular gait, the amplitude of the steps becomes larger and the duration of the limb cycle is reduced in order to repeat the limb movements more frequently. The stride frequency (SF) and stride length (SL) are the two main components of the gait speed. The mean speed (V) can be estimated by the product of the stride frequency by the stride length:  $V = SF \times SL$ . The velocity-related changes in stride parameters have been studied in many horse breeds and disciplines. The stride length increases linearly with the speed of the gait. The stride frequency increases non-linearly and more slowly (Dusek *et al.*, 1970; Leach & Cymbaluk, 1986; Ishii *et al.*, 1989). For a quick increase of running velocity, such as that occurring at the start of a gallop race, the stride frequency reaches its maximum value first to produce the acceleration, while the maximum stride length slowly reaches its maximum value (Hiraga *et al.*, 1994).

In Thoroughbred racehorses, the fatigue effect on stride characteristics increases the overlap time between the lead hindlimb and the non-lead forelimb, the stride duration and the suspension phase duration (Leach & Springings, 1987). The compliance of the track surface also can influence the stride parameters when the horse is trotting or galloping at high speed. At the gallop, the stride duration tends to be reduced on a harder track surface (Fredricson *et al.*, 1983). There is a slight increase in the stride duration on wood-fibre tracks in comparison with a turf track at the same speed. When the rider stimulated the horse with a stick, a reduction in the stride length and an increase in the stride frequency corresponding to a reduction of the forelimb stance phase duration were observed. However, the velocity was not significantly influenced (Deuel & Lawrence, 1987).

#### *Relationships between locomotion and other physiological functions*

Some relationships have been established between stride parameters and other physiological variables. At the canter and gallop, the respiratory and limb cycle are synchronized. The inspiration starts from the beginning of the suspension phase and ends at

the beginning of the non-lead forelimb stance phase. Expiration then occurs during the stance phase of the non-lead and lead forelimbs (Attenburrow, 1982). Expiration is facilitated by the compression of the rib cage during the weight bearing of the forelimbs. This functional coupling might be a limiting factor for ventilation at maximal exercise intensity. At the walk, trot and pace, there is not a consistent coupling of the locomotion and the respiratory cycle. At the trot, the ratio between locomotor and respiratory frequency ranged between 1 to 3 with respect to the speed, the duration of exercise and the breed (Hörnigke *et al.*, 1987; Art *et al.*, 1989). The same type of low coupling mechanism was observed at pace where the ratio between the stride and respiratory frequency could be 1 to 1.5 (Evans *et al.*, 1994).

The relationship between stride parameters at high speed and muscle fibre composition was studied in Standardbreds (Persson *et al.*, 1991). The stride length and frequency were extrapolated at a speed of equivalent to a heart rate of 200 bpm (V200) or  $V=9\text{m/s}$ . The stride length was positively correlated with the percentages of type I fibre (aerobic slow twitch fibre) and type IIA (aero-anaerobic fast twitch) fibre, and negatively correlated with the percentages of type IIB (anaerobic fast twitch) fibre. The stride frequency was only positively correlated with the percentage of type IIA fibres. However, in another study the opposite result was found: a negative correlation between the stance duration of young trotters and the percentage of type IIB fibres (Roneus *et al.*, 1995). For race trotters, the force-velocity relationship for skeletal muscles implied in limb protraction and retraction might be an important limiting factor of the maximal stride frequency (Leach, 1987). In Andalusian horses, there was no significant correlation between the stance duration and the fibre type percentages. However, the diameter of the fibres was negatively correlated with the stance duration (Rivero & Clayton, 1996). The propulsive force during the stance phase might be higher with larger fibres, especially type I.

During an exercise test, the blood lactate concentrations and heart rate at high speed seem to be more highly correlated with the stride length than to the stride frequency on the treadmill (Persson *et al.*, 1991; Valette *et al.*, 1992). This finding confirms that the high speed which elicited a high cardiac and metabolic response is mainly explained by an increase in stride length. Furthermore, the velocity

relating to change in stride frequency is not linear and consequently decreases the coefficient of correlation. In ponies tested on the track, the stride frequency was more highly correlated to the blood lactate and heart rate response than the stride length probably because of its narrow range in that species (Valette *et al.*, 1990).

#### *Gait development and training effect*

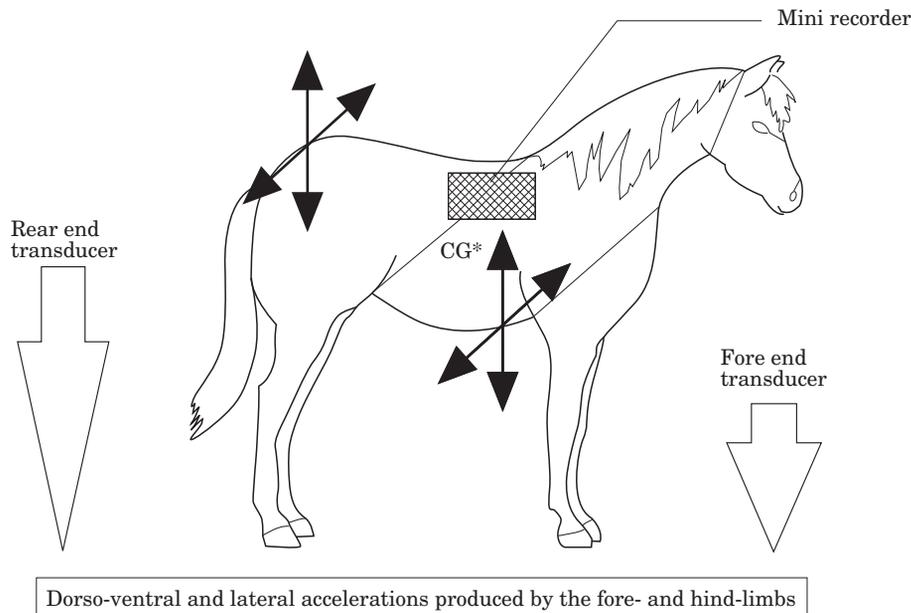
Gait patterns are influenced by the age of the horse, but little is known about gait development. Some studies have investigated the stride characteristics of foals and analysed the relationship between the conformation and the stride variables in foals aged 6–8 months. Speed increases were obtained by a longer stride length in heavier foals and a higher stride frequency in taller foals (Leach & Cymbaluk, 1986). The elbow, carpal and fetlock joint angle flexions were the most significant differences between the foals (Back *et al.*, 1993). The stride and stance duration increased with age, but the swing duration and pro-retraction angle were consistent. The joint angle patterns recorded at 4 and 26 months were nearly similar. The good correlations of some of the kinematic parameters measured in foals and adults make it possible to measure them in young horses in order to predict the gait quality of adult horses (Back *et al.*, 1994a).

In racehorses, the influence of training has been investigated in Standardbreds and Thoroughbreds. After 3 years of training, the following changes in the trotting strides were observed: the stride length, the stride duration and swing phase increased (Drevemo *et al.*, 1980). In Thoroughbred racing, a stride duration and stride length increase was found (Leach & Springings, 1987). After 8 weeks of a high intensity training regimen on a treadmill, the stance phase duration of the Thoroughbred gallop stride was reduced by 8–20% (Corley & Goodship, 1994).

## APPLICATIONS OF GAIT ANALYSIS

### *Lameness quantification*

Because of the great economical loss due to lameness and the difficulties in establishing a diagnosis, techniques of lameness quantification have been a research priority. Both kinematic and kinetic methods are now available to measure gait irregularities. In order to be more easily applicable under practice conditions, gait measuring techniques should be



**Fig. 4.** Quantification of lameness by using acceleration measurements. One transducer is fixed onto the sternum by means of an elastic girth and a second transducer onto the sacrum. The movements of the hind- and fore-limbs are recorded continuously by the accelerometers during a walking and trotting test.

increasingly simplified or specifically designed for horses. The methods do provide quantitative measurements of gait disorders, but the results are generally not specific to a given injury. The gait analysis system therefore should be used as a complimentary examination after the normal clinical examination.

Kinematic methods provide many descriptive parameters of joint mobility, such as the angle variations during the stride cycle. These types of analyses quantitatively describe the clinical signs. The high cost and the technical maintenance of a gait analysis system limit this type of application to the laboratory environment (Clayton, 1986; Deuel *et al.*, 1995; Galisteo *et al.*, 1997; Pourcelot *et al.*, 1997). The calculation of the accelerations of the head and sacrum make it possible to estimate two indexes of the gait symmetry (Kastner *et al.*, 1990; Buchner *et al.*, 1993; Uhlir *et al.*, 1997).

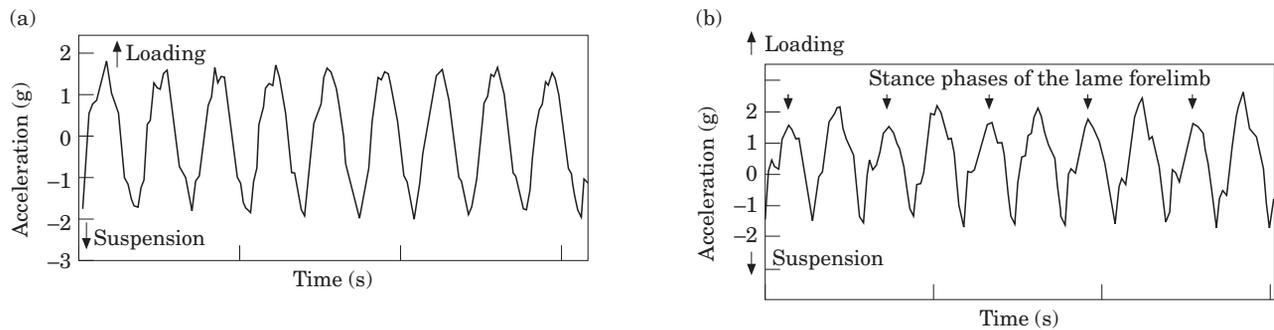
A force plate system imbedded in the track is used to measure ground reaction forces. It has been successfully used for characterizing, mainly supporting lamenesses such as superficial digital flexor tendonitis and distal joint injuries (Silver *et al.*, 1983; Merkens *et al.*, 1988a,b). One of the limitations of force plates is being able to control the location of the ground contact of the hooves. A major improvement was proposed recently by including a force plate under the surface of a treadmill belt

(Weishaupt *et al.*, 1996). This sophisticated device measured simultaneously the ground reaction forces of the four limbs and their point of application.

The measurement of the dorsoventral and transverse accelerations at the sternum using an ambulatory accelerometric recorder provided a measurement of the dynamic symmetry and regularity at the walk and trot (Barrey & Desbrosse, 1996). The location of the accelerometer at the sternum favoured the detection of forelimb lameness. Hindlimb lameness was better detected by fixing an additional accelerometer on the sacrum (Fig. 4). The degree of gait asymmetry and irregularity was related to the degree of lameness established by a clinical examination (Fig. 5). Both support and swing lameness can be detected because of the continuous acceleration measurements during several stance and swing phases of each limb. The advantage of this ambulatory technique is the simplicity and quickness of the testing procedure.

#### *Effect of shoeing and track design on limb biomechanics*

Many shoeing techniques are available, but any assumption concerning their biomechanical effects on hoof biomechanics should be verified experimentally by locomotion analysis studies. The limb



**Fig. 5.** Examples of dorsoventral (vertical) acceleration measured at the sternum of trotting horses. (a) A sound horse with a normal symmetry ( $\geq 97\%$ ) and regularity index ( $\geq 196/200$ ). (b) A lame horse (forelimb) with a low symmetry ( $= 94\%$ ) and regularity index ( $= 174/200$ ). Each vertical arrow indicates a reduction of the hoof loading during the stance phase of the lame forelimb (Barrey & Desbrosse, 1996).

kinematics of six sound horses was studied at trot in hand to determine the effect of long toes and acute hoof angles (Clayton, 1987). No lengthening of the trotting strides was observed after reducing the hoof angle by about  $10^\circ$  from the normal value. However, the significant alterations resulting in toe-first impact and prolonged breakover are potentially disadvantageous for athletic performance and may predispose the horse to injury.

The kinetics of the hoof impact is an interesting subject for lameness prevention, because a relationship between repeated exposure to shock and the onset of chronic injuries has been established in human medicine (Taylor & Brammer, 1982) and in animal models (Radin *et al.*, 1973, 1984). The shoes and the track surface can be designed in order to minimize the hoof shock intensity, especially for race and show jumping horses which undergo very large hoof decelerations at high speeds and landing, respectively. Hoof shock and vibration acceleration measurements after the moment of impact on the ground were used to investigate the damping capacity of various hoof pads and shoes (Benoit *et al.*, 1993). Compared to the reference steel shoe, the shock reduction was higher for light shoes made of a polymer and/or aluminium alloy, which had lower stiffness values and density than steel. The use of visco-elastic pads contributed to shock reduction and attenuated the high frequency vibrations by up to 75%.

The same acceleration measuring technique was applied for testing the influence of the track surface on the shock and vibration intensity of the hoof impact at the trot (Barrey *et al.*, 1991). The shock deceleration can reach high deceleration such as  $707\text{m/s}^2$  on asphalt; and the subsequent transient vibrations could reach 592Hz. The stiffness of the

track surface directly influences these mechanical parameters and should be controlled in order to minimize the vibration damage. In horses, as in human athletes, damping hoof impact with visco-elastic shoes and a short track surface is useful to prevent orthopaedic overuse injuries of the distal joints.

The improvements in race track designs and surfaces for racehorses is a typical example of an application of research which concerns the racing industry. The limb kinematic studies on Standardbreds trotting on various types of race tracks (length, curves) have made it possible to propose some recommendations to define the ideal geometry for race tracks (Fredricson *et al.*, 1975; Drevemo & Hjerten, 1991). The most important factor affecting comfort are the total length of the track, which determines the curve length, and the inclination, to avoid any load disequilibrium between the lateral and medial sides of the limbs.

#### *Relationships between locomotor variables and equine performances*

One of the challenges for equine exercise physiology could be to predict the performance potential of young horses by measuring physiological and locomotor parameters during a test. After validation, the use of this early measure of exercise ability could improve the economic efficiency of the horse industry and affect breeding techniques. In each discipline, some locomotor variables are related to competitive performance because they are one of the limiting factors. To improve breeding and reduce the costs of training, early performance evaluation tests for each discipline should be developed. For breeding applications, the genetic components of the locomotion parameters should

be investigated using standardized tests which are easy to perform under track conditions and allow collection of a large amount of data.

*Trotting races.* Good trotters show a short stance phase duration with a longer stance phase in the hind limbs than in the forelimbs (Bayer, 1973). A locomotor test performed in race trotters on a track confirmed that the best race performances were obtained by trotters that had the highest maximal stride frequency and a long stride length (Barrey *et al.*, 1995). These findings suggest that good race trotters are able to trot at high speed using an optimal stride length and that they can accelerate by increasing their stride frequency in order to finish the race.

*Galloping races.* The maximum gallop velocity is mainly explained by the stride length. An increase in this component is obtained by decreasing the overlap duration of the lead hindlimb and non-lead forelimb stance phase (Leach *et al.*, 1987). The movements of the hindlimbs and forelimbs are dissociated and the length between the footfalls of the diagonal increases. The overlap time of the diagonal decreases linearly down to about 50ms as the galloping speed increases (Hellander *et al.*, 1983; Deuel & Lawrence, 1984). In poorly performing Thoroughbreds tested on an inclined treadmill (10% slope) at a maximum velocity of 12m/s, the stride length and velocity at the maximum heart rate were the variables that were the most highly correlated to the run time on the treadmill (Rose *et al.*, 1995).

The analysis of the gallop stride characteristics of 3-day event horses during the steeplechase of the Seoul Olympic games revealed optimal values for successful performance. The optimal stride length should range between 1.85 and 2.05m while the optimal velocity should range between 13 and 14.3m/s (Deuel & Park, 1993).

*Show jumping.* During the 1988 Olympic Games, the kinematics of jumps over high and wide obstacle (oxer) were analysed in 29 horses, and the relationship to the total penalty score was studied (Deuel & Park, 1991). Few total penalties were associated with lower velocities during the jump strides, closer take-off hindlimb placements and closer landing forelimb placements. Another study on elite horses jumping a high vertical fence demonstrated that the push-off produced by the hind limbs at take-off explained most of the mechanical energy required for clearing the fence (van den

Bogert *et al.*, 1994). The action of the forelimbs should be limited to put the body of the horse into a good orientation before the final push-off of the hindlimbs. A more vertical component of the initial velocity was observed in the horses that successfully cleared a wide water jump (4.5m) (Clayton *et al.*, 1995). The angle of the velocity relative to the horizontal was 15° in a successful jump compared to 12° in an unsuccessful jump, and the vertical component of the velocity was about 0.5m/s greater in successful jumps than in unsuccessful jumps. This initial velocity was generated by the impulse of the hindlimbs and determined the ballistic flight characteristics of the body.

These kinematic findings agree with another study, which showed that poor jumpers had a lower acceleration peak of the hindlimb at take-off than good jumpers (Barrey & Galloux, 1997). Poor jumpers brake too much with the forelimbs as take-off impulse and the hindlimbs produce an acceleration which is too weak for clearing the fence. This force is one of the main factors affecting a jump success, because it determines the ballistic flight of the center of gravity and also the characteristics of the body rotation over the obstacle during the airborne phase. The moment of inertia and its influence on the body rotation was also studied in a group of jumping horses but no consistent relationship with the level of performance was found (Galloux & Barrey, 1997). More penalties were recorded for horses that cantered at a low stride frequency (lower or equal to 1.76 stride/s) and suddenly reduced their stride frequency at take-off.

*Dressage.* In dressage, the horse should execute complex exercises, gait variations and gait transitions while maintaining its equilibrium and suppleness. This discipline requires a high level of locomotor control by the rider which is obtained progressively through exercise and collecting the gaits. A horse's ability for collection seems to be one of the main limiting factors for dressage, because it is impossible to execute correctly the more complex exercises in competition without having attained a good collected gait. The collected gaits have been extensively described in kinematic studies (Holmström *et al.*, 1994a; Clayton, 1994, 1995; Burns & Clayton, 1997). Some locomotor parameters were identified as favouring collection ability, extended gaits and the expressiveness of the gait (Holmström *et al.*, 1994b; Back *et al.*, 1994). A slow stride frequency including a long swing phase is required for good trot quality. The elapsed time between the

hindlimb contact and the diagonal forelimb contact defines the diagonal advanced placement and should be positive and high at the trot. The horse should place its hindlimbs as far as possible under itself. The vertical displacements of the body during collected gaits is also an important factor. For extending the trot, having an inclined scapula (conformation) and the amplitude of the elbow joint appeared as important factors. The horses judged to have a good trot should have a large flexion in the elbow and carpus joints at the beginning of the swing phase. A longitudinal study revealed that the duration of the trot swing phase, the maximal range of protraction–retraction of the limbs and the maximal flexion of hock joint were well correlated between 4 to 26 months of age (Back *et al.*, 1994b).

The relationships between the total score and the canter characteristics in Olympic dressage horses showed that the best horses were able to extend their gallop strides by increasing their stride length without changing their stride frequency (Deuel & Park, 1990). For 3-day-event horses at the Olympic games, extended canter stride length and velocity were positively related to points awarded by judges. However, non-finishers of the event had higher extended canter stride lengths and velocities in the dressage phase than finishers (Deuel, 1995).

### Conclusion

All the body systems are linked to generate the muscular and, finally, the mechanical work involved in locomotion. Equine gait analysis is a complementary approach combining metabolic, cardiorespiratory and muscular investigations in order to understand factors influencing performance. Currently, the great improvement in sensor and image analysis technology make it possible easily to apply kinetic and kinematic techniques in laboratories and under track conditions. After extensive fundamental and methodological research on the various aspects of equine locomotion, equine biomechanics is now a mature science and should provide practical applications for lameness quantification and prevention, as well as shoeing, training and performance evaluation. It is very important that the scientific community also consider applied research projects and popularize the new findings for the horse industry.

Since Leach and Crawford (1983) described potential guidelines for future equine locomotion research, many of the described objectives have been reached. However, the number of concrete

applications available for trainers, riders, breeders and veterinary practitioners is too limited compared to the amount of work that has been done. To improve this situation for gait quantification and performance evaluation, a great technological effort is needed using all the knowledge that has been obtained in equine locomotion to create applications that can be used under field conditions.

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