3

Measurement Techniques for Gait Analysis

Hilary M. Clayton and Henk C. Schamhardt

INTRODUCTION

In daily life, almost everybody is using gait analysis, often without realizing it. While walking in the street, it usually takes only a fraction of a second to determine whether an approaching person is male or female, and whether that person is familiar or a complete stranger. The human eye, which captures the image, and the human brain, which processes it, are a surprisingly powerful system for recognition and identification. After a little training, the human observer is also able to judge the quality of gait: one can determine whether a particular walking pattern is supple and graceful or clumsy and incoordinated. This statement holds true not only for observations of people moving in various activities (walking or running, dancing or sport), but also for judging the performance of animals.

The eye of the experienced judge determines the outcome of equestrian sports such as dressage, reining, cutting and show hunters. Selection of horses for inclusion in breed registries and for approval as breeding stock is also based, to a certain extent, on the opinion of a committee of judges. However, this kind of 'gait analysis', based on the judgement of an observer carries all the risks that are inherent in subjectivity.

Qualitative gait analysis is also applied successfully in the diagnosis of equine lameness. Clinicians use a semi-quantitative method of evaluation when assigning a lameness grade. While repeatability of lameness scores within an experienced clinician may be good (Back *et al.*, 1993), there is considerable variation between clinicians (Keegan *et al.*, 1998).

However, there are applications for which a qualitative evaluation of locomotion is inadequate, necessitating the use of a quantitative method of analysis that offers greater accuracy without the biases that are inherent in a subjective analysis. Chapter 1 provided an eloquent description of the evolution of different methods of gait analysis, and the explosion of research studies that have exploited the new capabilities for data storage and data processing in the computer age. This chapter will describe the current and emerging techniques for equine gait evaluation in the areas of kinematic analysis, kinetic analysis, electromyography and computer modeling. The value of the treadmill for data collection will also be considered.

Kinematic analysis measures the geometry of movement without considering the forces that cause the movement. At the present time, the majority of kinematic evaluations are performed using videographic or optoelectronic systems consisting of integrated hardware and software components. Kinetics is the study of the forces that are responsible for the movements. A variety of transducers, including strain gauges, piezoelectric and piezoresistive transducers and accelerometers, are used in kinetic studies. Several transducers can be combined to develop force plates and force shoes for measuring ground reaction forces (GRFs). Electromyography detects the electrical activity associated with muscular contraction as a means of determining muscular activation patterns during different activities. The variables that are measured during gait analysis can be used to compute other quantities that are not or cannot be measured directly through computer modeling. The development of appropriate models facilitates a deeper understanding of the behavior of the musculoskeletal system and allows predictions to be made regarding its response to various perturbations without the need for live animal experiments.

INTERPRETING THE EFFECTS OF BIOLOGICAL VARIABILITY

It is widely recognized that a certain variability is inherent to data obtained from repeated measurements on biological material, and it is necessary to give consideration as to how to treat these data correctly. As an example, consider the measurement of GRFs using a force plate. When the horse is guided over the force plate, the chance for a correct hit by one fore hoof is about 50%, with the number of hits being approximately evenly distributed between the right and left limbs. After several runs, it is likely that a different number of correct hits will have been recorded from the right and left limbs. When calculating the mean and the standard error of the mean (SEM) for a force variable (e.g. peak vertical force) by averaging the data of these runs, the mean of the data obtained from the limb with the higher number of correct hits usually has a lower SEM. Are data from that limb more 'correct' than those from the other limb? Obviously not, but it is not easy to define a universal, statistically correct recipe to deal with this problem. In practice, most laboratories collect data until a certain minimum number of correct hits have been recorded from each limb. In sound horses, both the kinematic and force variables are quite stable, and analysis of a relatively small number of strides is representative of the gait pattern. It has been suggested that 3–5 strides are sufficient for kinematic (Drevemo *et al.*, 1980a) or GRF (Schamhardt, 1996) analysis. The data describing an equal number of strides for each limb are averaged and considered to be 'representative' for that limb. The mean value is then used in further stages of the analysis as being representative of that variable for a particular limb in one horse. Most of the stride variables show good repeatability over the short and long term (Drevemo *et al.*, 1980b; Weeren *et al.*, 1993), and the stride kinematics of a young horse have already assumed the characteristics that they will have at maturity by the time the foal is 4 months of age (Back *et al.*, 1994).

Variability between individual horses affects the response to certain interferences, such as drug treatment and shoeing, which differ qualitatively and quantitatively in different animals. Impressive libraries of statistical routines have been developed to extract trends in the data, to detect differences between groups, or to identify a 'statistically significant' response to a certain treatment. Unfortunately, the prerequisites for these statistical tests may invalidate their use in a particular study. For example, data may not be normally distributed, or data describing different variables may be correlated with each other. Therefore, it is very important to plan the experiment and treat the data in a statistically appropriate manner. Before any experiment is carried out, a thorough evaluation of the problem should be conducted. An hypothesis is formulated, and an appropriate experimental design and statistical model are determined to test that hypothesis. After collection of data, it is not unusual to find dependency within series of data, which disqualifies a particular statistical test. A detailed discussion of the pitfalls and problems associated with statistical testing is beyond the scope this text. Readers are advised to consult a suitable statistical text or a statistician to avoid using incorrect analyses, which have appeared frequently in the literature.

A statistical test determines the likelihood that a certain hypothesis can be accepted, or has to be rejected. However, the answer is not absolute: for example, having selected an uncertainty level of $p < 0.05$, the correct decision to accept or reject the hypothesis will be made in 95% of cases. Conversely, there is a 5% chance of being wrong, and one observation out of 20 will differ significantly due to chance. Therefore, statistical tests are not proof that a certain hypothesis is true or false. The majority of equine locomotion studies are based on a rather small number of subjects, which may be insufficient to give the required power for a statistical analysis. In these cases, trends in the data may suggest a biologically significant effect that cannot be proven statistically but is, nevertheless, important.

Summary

Summary statistical analysis of biological data is important, but rather difficult to perform correctly and the literature contains many examples of incorrect applications. Furthermore, it is not only the statistical significance or lack thereof that is important in interpreting the results of a study; the findings should also be interpreted in terms of trends that are indicative of the biological relevance of the outcome.

KINEMATIC ANALYSIS

Kinematic analysis quantifies the features of gait that are assessed qualitatively during a visual examination. The output is in the form of temporal (timing), linear (distance) and angular measurements that describe the movements of the body segments and joint angles. The data may be transferred to a spreadsheet for further analysis, e.g. detection of asymmetries between lame and sound limbs, or it may be displayed graphically or as stick

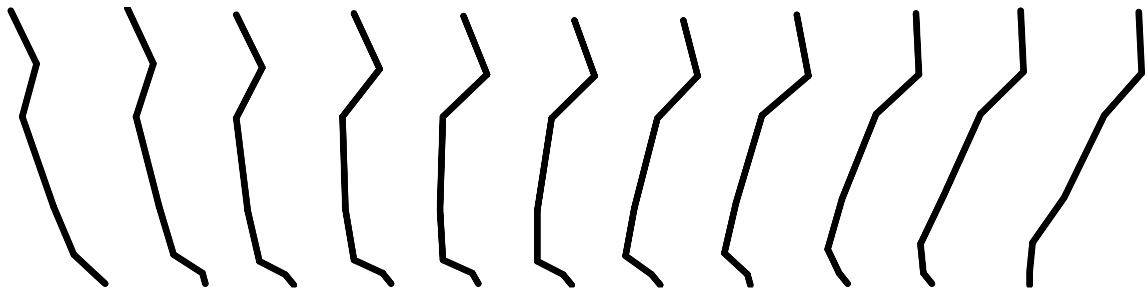

Fig. 3.1 Stick figure of the forelimb of a horse trotting overground. The figures are shown at intervals of 10% of stance duration.

figures (Fig. 3.1). In the past high speed cinematography was the most commonly used technique for kinematic analysis, but it was an expensive and tedious method. TrackEye (Innovativ Vision AB, Linköping, Sweden) is an image digitizing system that usually processes high speed film to provide accurate two dimensional data with software for three dimensional reconstruction. Today, the most popular techniques for studying kinematics are videographic analysis combined with a commercial software package, or optoelectronic systems that are based on the emission and detection of infrared or visible light. Analyses may be two dimensional or three dimensional. Two dimensional studies are relatively simple to perform but the results are adversely affected by image distortion due to out-of-plane image movements of the body segments. Three dimensional analysis overcomes these problems, but is a more complex procedure, particularly with regard to calibration of the movement space.

Videographic systems

Videography is a popular method of kinematic analysis in horses. Turnkey systems are available that produce useful data within a reasonable period of time by autodigitising reflective markers on the subject either on-line or during post-processing. However, the user must check the accuracy of the digitisation before accepting the data for further analysis. Problems arise when different markers cross each other in the field of view or when a marker is temporarily obscured. Errors in the raw data will give rise to problems throughout the subsequent analysis. Some video systems also offer a manual digitising option that can be used when there are no markers on the subject, for example when videos are recorded during a competition. Manual digitising is also a useful option when the autodigitising system has difficulty differentiating between markers that are placed close together or that cross each other during locomotion.

The sequence of events for video analysis involves marker application to the subject, setting up and calibrating the recording space, video recording, digitisation, transformation, smoothing and normalisation. Analyses may be performed in two or three dimensions. Since the limbs of the horse have evolved to move primarily in a sagittal plane, most of the useful information is captured by the two dimensional lateral view, and in many situations the extra effort involved in extracting three dimensional data is not warranted. However, there are times when a knowledge of the abduction and adduction or internal and external rotations would be useful, especially during sporting activities and in relation to lameness. Most video systems are capable of three dimensional analysis, but there are some additional requirements beyond those for two dimensional analysis. These include using a minimum of two camera views and ensuring that each marker is visible to at least two cameras throughout the movement.

Video-based kinematic analysis systems used in horses include the Ariel Performance Analysis System (Ariel Dynamics Inc, Trabuco Canyon, CA), ExpertVision (Motion Analysis Corp, Santa Rosa, CA), and Peak Performance System (Peak Performance Technologies Inc, Englewood, CO).

Skin markers

Most video systems offer automated digitisation if appropriate markers are placed on the skin and the lighting is controlled to provide sufficient contrast between the edge of the markers and the surroundings. Black acrylic paint, available from artist's supply stores, can be used to draw a bullseye target around a marker to improve its contrast against white hairs. For two dimensional analysis, circular markers, 2–3 cm in diameter are used, with the bigger markers giving better accuracy when the resolution of the system is poor (Schamhardt *et al.*, 1993a). Retro reflective material can be purchased in sheets

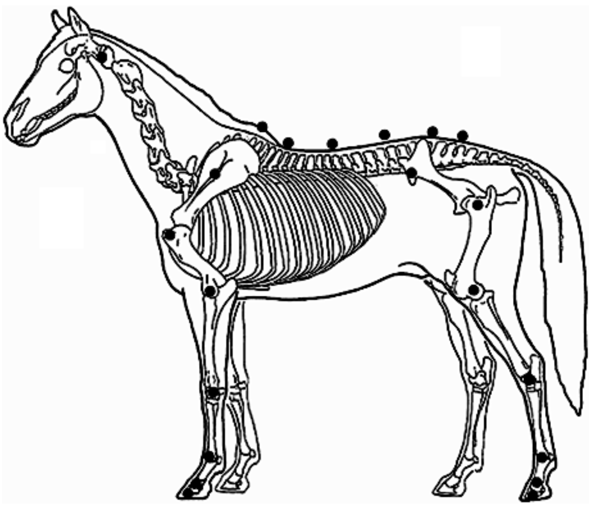

Fig. 3.2 The black dots represent locations that are commonly used for skin marker placement for kinematic analysis.

(Scotchlite, 3M Corp, St Paul, MN) and cut into markers of a suitable size or precept circles can be purchased at a higher price. The self-adhesive backing may not be adequate to hold the markers in place, especially when the horse sweats. Cyanoacrylate glue (super glue) is effective for securing the markers, but some brands are difficult to remove completely at the end of the study, which may pose a problem in client-owned horses. A little experimentation may be needed to find appropriate products for use under a variety of circumstances. Retro reflective paint (Scotchlite 7210 Silver, 3M Corp, St Paul, MN) is also available, but the reflective beads tend to clump, making it a less satisfactory method of marking. For three dimensional studies spherical or hemispherical markers are used because they retain their circular shape when viewed from different angles. Spherical markers can be purchased ready-made or they can be made from polystyrene balls, about 3 cm in diameter, which are purchased from hobby stores. If necessary, the balls are cut in half before covering them with strips of reflective tape or reflective paint.

Marker locations are chosen in accordance with the purposes of the analysis. Calculation of the angle between two limb segments in two dimensions requires a minimum of three markers. Figure 3.2 shows the approximate centers of joint rotation on the fore and hindlimbs, which can be used for marker placement during two dimensional analyses in the sagittal plane, using software packages that require the markers to be placed over the joint centers. Other software allows the use of two markers per segment that are aligned along the long axis of the segment, without necessarily being placed over the joint centers. Markers on the dorsal midline of the back are used to evaluate trunk motion (Licka & Peham, 1998). Markers on the neck, withers and croup are useful for evaluating left-right asymmetries in the vertical excursions of these reference points.

On the limbs, skin movements relative to specific underlying bony landmarks has been quantified and correction algorithms have been developed for walking and trotting Dutch warmblood horses (Weeren *et al.*, 1990a, 1990b, 1992). However, these algorithms are only valid for horses of similar conformation, moving at the same gaits and at similar speeds. Figure 3.3 illustrates the effect of skin displacement on the angular motions of the stifle and tarsal joints during walking. It shows that the effects of skin movement are much greater at the stifle joint than at the tarsal joint. Distal to the elbow of the forelimb and the stifle of the hindlimb, skin movement artifact is small enough to be neglected. In the more proximal parts of the limb, however, skin movements as large as 12 cm have been measured, which is sufficient to change the entire shape of the angle-time diagrams at the proximal joints. In these locations, uncorrected data cannot be used for absolute angular computations or for measuring muscle or tendon lengths based on limb kinematics.

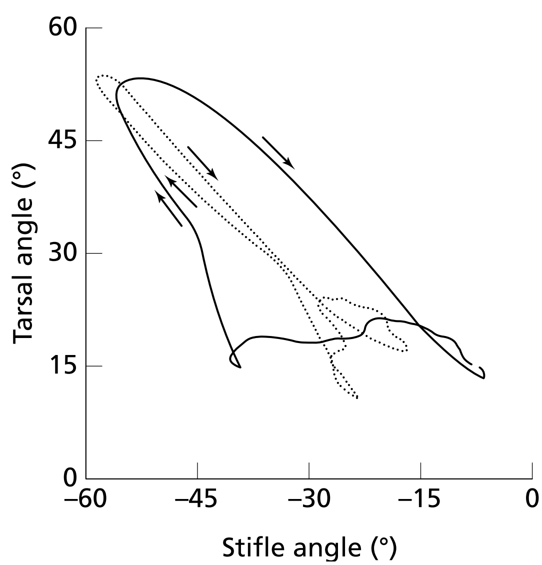

Fig. 3.3 Angle-angle diagrams of the stifle and tarsal joints of a horse at the walk. The movements of the skin markers are shown before (continuous line) and after (broken line) correction for skin displacement. (Reprinted with permission from Schamhardt, H.C. (1996) In: *Measuring movement and locomotion: From invertebrates to humans*).

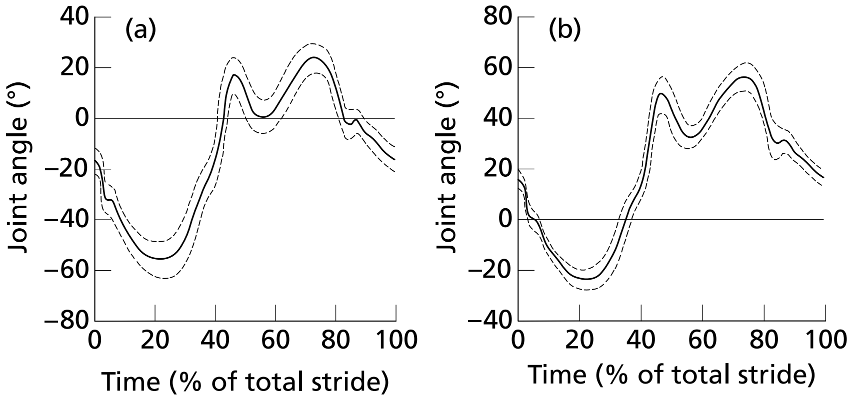

Fig. 3.4 Angle-angle diagrams of the fetlock joint of the forelimb of a horse trotting on a treadmill at 4 m/s. The diagram on the left shows the joint angles measured relative to the position in which the proximal and distal segments are aligned. The diagram on the right shows the angles relative to those recorded with the horse standing squarely. For both diagrams flexion is positive and extension is negative. (Reprinted with permission from Schamhardt, H.C. (1996) In: *Measuring movement and locomotion: From invertebrates to humans*.)

The repeatability in positioning the skin markers must also be considered. Usually, markers are applied in the standing horse and care should be taken that the horse is standing squarely with weight on all four limbs. When the limb is unloaded or when the horse is not standing still, it is difficult to fix the markers with an accuracy better than about 0.5 cm. Inevitably, this has consequences for repeated measurements in one horse, when the markers have to be removed between sessions, unless remnants of glue remain or paint is used to mark the spot. Another possibility for avoiding this problem is to standardize joint angular measurements to those obtained in the square standing horse (Back *et al.*, 1994), so that the angles are reported as deviations from this square standing position, with relative flexion being assigned a positive value and relative extension being assigned a negative value. Repeated measurements of horses positioned in a square standing position, however, have indicated poor reliability (Sloet, personal communication). Other methods of displaying joint angles include reporting the absolute joint angle, which is usually measured on the anatomical flexor aspect of the joint, or measuring the flexion (positive) and extension (negative) angles relative to the position at which the proximal and distal segments are aligned. Although the patterns are the same regardless of the method of measurement (Fig. 3.4), the values differ considerably, which impairs comparisons between data from different studies.

The requirements for three dimensional analysis are similar to those for two dimensional analysis in that the chosen marker locations show minimal skin displacement or have correction algorithms to compensate for skin displacement. In addition, each marker must be visible to at least two cameras throughout the movement. This combination of requirements is difficult to fulfil during some movements. One way to overcome these problems is to use a virtual targeting system (Nicodemus *et al.*, 1999). This method relies on the fact that, for rigid body motion, the location of any point on a body does not change with respect to that body. Therefore, if the location of a point on a segment is known with respect to the segment, and the orientation of the segment is known in a global coordinate system, then the location of that point on that segment can be calculated in the global coordinate system. The virtual targeting method employs two sets of markers: tracking markers and virtual markers. Three virtual markers are attached to each segment to define the segmental coordinate system: two are oriented along the long axis of the segment and the third is perpendicular to that axis. Three non-collinear tracking markers are placed on the segment in appropriate positions to track the motion of the segment in the global coordinate system, i.e. at locations that are readily visible to the cameras during locomotion and at locations for which the skin displacement is known. The coordinates of the tracking markers are used in a transformation that converts the global coordinate system to a segmental coordinate system. A standing file is recorded with both the virtual and tracking markers in place (Fig. 3.5), after which the virtual markers are removed. Recordings are made with the tracking markers in place. During the subsequent data processing, algorithms are used to calculate the locations of the virtual markers with respect to a segmental coordinate system and to track that target in the global coordinate system (Lanovaz *et al.*, submitted).

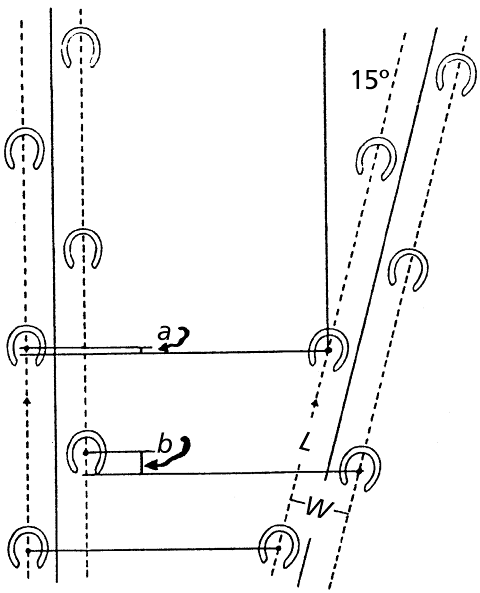

Fig. 3.5 Influence of the horse moving obliquely across the force plate, at an angle of 15° to the long axis of the plate. The erroneously calculated stride length (L* cos α = L* 0.9) differs from the actual length *L* by the distance *a*, which is fairly small. The calculated placement of the right limb in front of the left limb is much more affected (distance *b*), because *b* is proportional to w * sin α = w * 0.26. (Reprinted with permission from Schamhardt, H.C. (1996) In: *Measuring movement and locomotion: From invertebrates to humans*.)

Video recording

For two dimensional studies, the camera is precisely oriented so that its axis is perpendicular to the plane of interest. For three dimensional studies, precise camera positioning is not important, so long as each marker is visible to at least two cameras at all times. However, if the angle between the cameras is small, it reduces the accuracy along the axis running toward the cameras. The field of view should always be somewhat larger than the movement space to avoid errors due to distortion at the periphery of the lens, especially with a wide angled lens.

An important decision relates to the type of video camera to be purchased and whether it is worth investing in a high speed camera. A standard camcorder records 30 frames/s in the NTSC format and 25 frames/s in the PAL format. Each frame is made up of 2 video fields recorded 1\60s (NTSC) or 1\50s (PAL) apart. The gait analysis software may be able to display successive fields sequentially giving an effective sampling rate of 60 fields/s (NTSC) or 50 fields/s (PAL). High speed video cameras are available and are useful for studies of short duration events or rapid movements but the lighting conditions become more critical at faster recording speeds. Comparisons of joint displacement data from horses cantering on a treadmill showed minimal loss of information in terms of angular data when the sampling rate was reduced from 200 Hz to 50 Hz (Lanovaz, unpublished). Linford (1994) compared the temporal stride variables in horses trotting on a treadmill by analysing the same ten strides with two cameras sampling at 60 Hz and at 1000 Hz, respectively. Mean values for stride duration, stance duration, swing duration, and breakover did not differ by more than more than 3.3 ms. A camcorder that records at 60 Hz is adequate for kinematic analysis of some aspects of equine locomotion, but a large number of strides must be analysed to produce a representative mean value for temporal events of short duration. At gaits faster than a walk, a faster camera is preferable, especially the displacement data will be processed further.

During a recording session the markers on the horse are illuminated by a lamp (usually 300–500 Watts) directed along the axis of the lens. If there is too much ambient light, it may not be possible to autodigitize the markers, so controlled lighting conditions are an advantage. When the exposure time is very short, as when using high speed cameras, more illumination is needed to maintain decent quality of the video image.

Calibration

A calibration frame is recorded in the field of view to scale the coordinate data. For two dimensional analysis, a rectangular frame or a linear ruler is positioned along the horse's line of progression. If the horse deviates from the plane of calibration but continues to move parallel to the intended plane of motion, errors are introduced in the linear data, though the timing data are not affected. Correction algorithms can be used to adjust the linear data if the horse moves along a line parallel to the intended plane of motion. However, if the horse moves at an oblique angle to the camera, it causes image distortion. Length measurements along a line in the longitudinal direction (e.g. stride length) are proportional to the cosine of the angle at which the horse moves relative to the desired direction (Fig. 3.5). As long as the oblique movement angle is less than about 15°, this error is smaller than 5%. If a transverse distance is involved, such as step length between the left and right limbs, the distances show a larger error that is proportional to the sine of the oblique movement angle. Again, assuming the horse moves at an angle of 15°, the error in the transverse direction can be as large as 26% (Fig. 3.5).

For three dimensional studies a calibration frame with non-coplanar control points is used. A larger number of control points gives a more accurate reconstruction. The accuracy of the data is markedly reduced outside the area of volume of the calibration frame, so a large, custom designed frame is required for equine studies. The accuracy of the calibration completely determines the accuracy of the final three dimensional data (Deluzio *et al.*, 1993), which emphasizes the importance of investing the necessary effort into calibration of the volume space in which the measurements are made.

Digitization

Through the process of digitization the coordinates of the body markers are determined in two dimensional or three dimensional space. Digitization may be performed manually, or it may be performed automatically with the system locating each marker by edge detection then calculating the position of its center. If the software allows, it is preferable for the operator to check each digitized field and make adjustments for digitizing errors or invisible markers before accepting the data into memory. In some situations, for example when there is too much ambient light or when markers cannot be applied as in a competition, manual digitisation is necessary. In addition to the time required, this tedious process creates more digitising noise than automated digitisation.

Transformation

The transformation process integrates the calibration information with the digitised coordinates to scale the data. For three dimensional studies Direct Linear Transformation (DLT) is the standard procedure for combining two or more two dimensional views into a single three dimensional view. This method has the advantage of not needing any information about camera locations; the transformation is based on knowledge of the coordinates of the control points on the calibration frame, which are determined for each camera view.

Smoothing

During digitisation small errors are introduced that constitute ‘noise’ in the signal. The effect of noise is not too great in the displacement data, but it becomes increasingly apparent in the time derivatives, i.e. the velocity and acceleration data (Fioretti & Jetto, 1989) as shown in Fig. 3.6. Smoothing removes high frequency noise introduced during the digitization process using one of two general approaches: a digital filter followed by finite difference technique or a curve fitting technique (e.g. polynomial or spline curve fitting). Selection of an appropriate smoothing algorithm and smoothing parameter for a specific purpose requires some expertise. As a guideline, a low pass digital filter with a cut-off frequency of 10–15 Hz is adequate for most videographic studies of equine gait. However, the movement of a market may have an oscillatory component, especially when loose connective tissue is interposed between the skin and the underlying bones. Since these oscillations are essentially tied to the movements themselves, they cannot be removed by smoothing (Schamhardt, 1996).

Normalization

Normalization or standardization of data facilitates comparisons between different horses by standardizing certain parameters. Normalization to the stride duration expresses the values of the temporal variables as a percentage of stride duration. This facilitates comparisons between strides that have slightly different durations, and allows the construction of mean curves from a number of strides. In other studies, normalization to stance duration or swing duration may be more appropriate depending on the objectives of the study. The most common method of performing the normalization is to use cubic spline interpolation, which resamples the curve at a set number of intervals (usually 100 or 101).

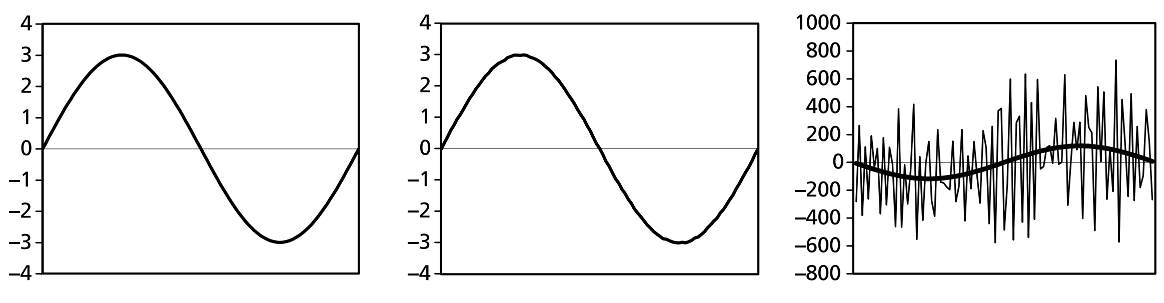

Fig. 3.6 Effect of noise on derived functions. The graphs show a smooth curve (left) to which a small amount of noise has been added (center) and the second derivative from the smooth (——) and noisy (—) data (right).

Optoelectronic systems

Many aspects of data collection and data processing using an optoelectronic system are similar to those described above for videographic systems. Procedures such as marker attachment, smoothing and normalisation of data that have been described for videographic analysis will not be repeated here.

Several systems are available that use either active markers (markers that emit a signal) or passive markers (markers that detect or reflect a signal). Use of these systems is usually confined to the laboratory, because of the need for a hard-wired connection to the subject and/or controlled lighting conditions. Optoelectronic systems are suitable for equine research include MacReflex and ProReflex (Qualysis Inc, Glastonbury, CT), Optotrack and Watsmart (Northern Digital Inc, Waterloo, ON), Selspot Motion Measurement System (Innovision Systems, Warren MI), Vicon (Oxford Metrics, Oxford, England) and CODA (Charnwood Dynamics Ltd, Barrow-upon-Soar, England). These systems perform the digitising on-line, so data are usually available quite quickly. Many of the systems have a built-in method for distinguishing between individual markers, for example by sequencing the temporal output of different markers or by using markers of different shapes or colors. The loss of direct control of digitising sometimes leads to errors in the data, especially in the systems that don't distinguish between markers.

The CODA system used for many of the studies at Utrecht University is one of a kind, having been modified from the original CODA-3 system (Schamhardt *et al.*, 1992). It tracks up to 12 markers simultaneously in three dimensional space with a sampling frequency of 300 samples/s. The markers are connected by a long umbilical cord to the portable scanner unit that consists of three light sources fixed to a steel frame. An advantage of the CODA system is that it does not need to be calibrated prior to each use because the coordinates are calculated relative to the frame of the scanner. At a measuring distance of 8 m, the accuracy in the transverse plane is about 0.3 mm.

MacReflex and ProReflex are used in a number of equine gait analysis labs. They are relatively easy to use and provide data rapidly without the need for digitisation. However, they do require a controlled lighting environment.

Electrogoniometry

An electrogoniometer or elgon is a device for measuring joint angle changes. It consists of a potentiometer attached to two rotating metal arms. These arms are fixed to the limb with tape or straps, so that the center of the elgon lies over the center of rotation of the joint (Fig. 3.7). Joint angle changes alter the electrical resistance of the potentiometer, which is calibrated with a protractor to produce a proportional displacement of known magnitude. Permanent records, or goniograms, can be recorded on an oscilloscope. The data can be stored in a computer for later analysis.

In horses, electrogoniometry has been used to record joint movements at different gaits in normal and lame horses (Adrian *et al.*, 1977), to diagnose obscure lameness, and to evaluate the changes in joint motion after medical or surgical treatment (Taylor *et al.*, 1966; Ratzlaff *et al.*, 1979).

Kinematic data

Kinematic data consist of temporal, linear and angular variables. Temporal data, which describe the stride duration and the limb coordination patterns, are calculated from the frame numbers and the sampling frequency. Distance data, computed from the coordinates of the markers combined with the calibration information, describe the stride length, the distances between limb placements, and the flight paths of the body parts. Angular data describe the displacements, velocities and accelerations of the body segments and joints.

In two dimensional studies the angular data are usually reported as flexion and extension in the sagittal plane. This is a reasonable simplification because the horse's joints have evolved to swing primarily in this plane as an energy-saving mechanism. The centers of joint rotation in the sagittal plane have been described (Leach & Dyson, 1988), and these locations are often used as land-

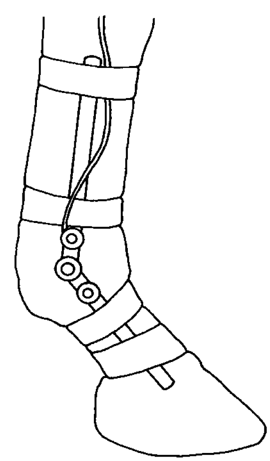

Fig. 3.7 Electrogoniometer placed over the equine fetlock joint.

marks for placement of skin markers for kinematic analysis (Fig. 3.2).

In three dimensional analysis the problems of standardization become much more complicated. First, each length measurement has three components in space and a segment requires three angle measurements to define its orientation. One approach that has been used in equine studies is to define the joint angles with the same landmarks used in the two dimensional studies and project the joint angles onto three mutually perpendicular planes that are tied to the global coordinate system (Fredricson *et al.*, 1972). Providing that the horse is moving in a direction parallel to a global coordinate axis, the planes become the sagittal, frontal and transverse planes. In effect, this method degrades the three dimensional analysis into a quasi-two dimensional analysis. This type of analysis is limited by the fact that joint motion that is not parallel to one of the projection planes cannot be accurately measured. Additionally, since this method usually defines segments as simple lines between landmarks, rotations along the long axis of a segment is impossible to measure.

An alternative is to establish a three dimensional joint coordinate system for the equine joints that is based on the axes of the limb segments, which are independent of the joint centers of rotation. This allows the true measurement of three types of joint motion; flexion/extension, adduction/abduction, and internal/external rotation.

Establishment of a three dimensional joint coordinate system requires that an axis system be defined for each limb segment that corresponds to an anatomically meaningful direction, such as the long axis of the bone. The segments themselves are defined by a minimum of three landmarks each. With one method of calculating joint angles (Grood & Suntay, 1983), an appropriate axis on the proximal segment of a joint is used as the flexion/extension axis and an axis on the distal segment becomes the internal/external rotation axis. The adduction/abduction axis is then defined as perpendicular to both the flexion/extension axis and the internal/external rotation axis. This is sometimes called the floating axis since it is not necessarily aligned with the planes of either limb segment. The three joint angles are usually expressed as motions of the distal segment relative to the proximal segment (Fig. 3.8) and the angles can be expressed independently of each other. This allows for examination of complex coupled motion in a joint.

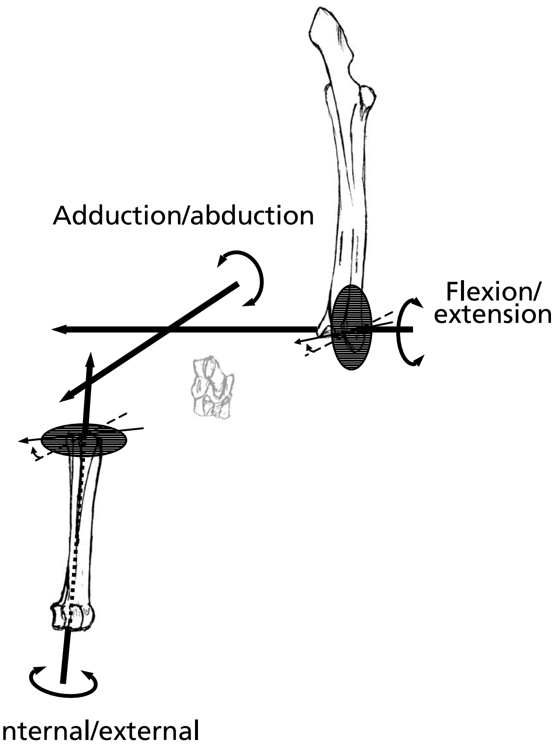

Fig. 3.8 Three dimensional joint coordinate system for kinematic analysis. Flexion/extension and external/internal rotation are expressed in terms of the distal segment rotating relative to the proximal segment. Abduction and adduction are relative to the floating axis.

KINETIC ANALYSIS

Kinetic analysis measures locomotor forces, both external and internal to the body. Forces developed by muscles are transformed into rotations of the limb segments that ultimately produce movement. The GRFs during locomotion can be recorded using a force plate (Pratt & O'Connor, 1976) or a force shoe (Frederick & Henderson, 1970; Ratzlaff *et al.*, 1990; Roepstorff & Drevemo, 1993). Transmission of forces and accelerations through the body are recorded by strain gauges and accelerometers attached directly to the tissues. Intrinsic forces in other parts of the locomotor system are calculated from a knowledge of the GRFs.

Force shoes

A force shoe is attached directly to the hoof and allows the GRF to be recorded during a large number of successive stance phases, which overcomes one of the limitations of the force plate. Force shoes also have the advantages of being amenable to use on different surface types, and being able to collect data from more than one limb at a time. Several researchers have used force shoes experimentally, but none is currently marketed commercially.

Frederick and Henderson (1970) described a device with three force sensors sandwiched between a base plate that was nailed to the hoof wall and a ground plate that was attached to the base plate, thus preloading the force sensors. Some years later, a force shoe designed at Washington State University was based on a piezoelectric transducer located in a housing over the frog. A later version with three transducers located at the medial heel, the lateral heel and the toe, gave a better correlation with simultaneous force plate recordings. It was used primarily in studies of galloping Thoroughbreds (e.g. Ratzlaff *et al.*, 1990), and provided unique data when a horse wearing the shoe sustained a rupture of the distal sesamoidean ligaments while galloping on a training track (Ratzlaff *et al.*, 1994).

A Swedish force shoe based on three strain gauge measuring units, one at the toe and one at each quarter, measures vertical, longitudinal and transverse forces (Roepstorff & Drevemo, 1993). The output has been shown to correlate well with that of a force plate, provided all three measuring units are in contact with the ground. When one or more sensors lose contact with the ground, for example during breakover, the force shoe and force plate signals do not compare well with each other. This shoe has been used to compare GRFs during exercise on treadmill belts with different compositions (Roepstorff *et al.*, 1994). Yet another type of force shoe, this time with four transducers, one on each side of the toe and quarters, was integrated into the bottom of an easy boot (Barrey, 1990).

Although a force shoe would be an ideal method of measuring GRFs, the technical difficulties in constructing an accurate and reliable device have restricted their use to the laboratories in which the various models have been developed. To date, the majority of published GRF data have been derived from force plate studies.

Force plate

A force plate is a steel plate, recessed into the ground then covered with a non-slip material (Fig. 3.9). When a horse steps on the plate, the force is detected by transducers at its corners, and is converted to an electrical signal that is amplified and recorded. Variables measured by the force plate include the stance duration, the magnitude of the vertical, longitudinal (horizontal craniocaudal) and transverse (horizontal mediolateral) forces, the time when the peak forces occur, the impulses (area under the force time curves), and the point of application of the force (center of pressure).

Selection and installation

In selecting a force plate for equine use, it is important to choose one that has a linear response over an appropriate range of forces, taking into account the weight of the horses and the gaits and speeds to be studied. The dimensions of the plate should maximize the chance of getting a good strike from one fore hoof followed by the hind hoof on the same side at a walk or trot. If two hooves strike the plate simultaneously, it is not possible to separate their effects, and the trial must be discarded. Shorter force plates (60–90 cm) are preferred for collecting data at the walk, but a length of 90–120 cm is preferable for use at the faster gaits. Width of the plate is

Fig. 3.9 Horse stepping on a force plate during data collection.

not generally a limiting factor, 50–60 cm is adequate. A good strike has been recorded for every 2–6 passes at the walk, trot and canter (Niki *et al.*, 1982; Merkens *et al.*, 1986, 1993a, 1993b). During jumping the obstacle is moved to increase the likelihood of getting a good strike with a particular limb at take off or landing (Schamhardt *et al.*, 1993b). The horse should move parallel with the long axis of the force plate to avoid cross talk between the horizontal transducers (Fig. 3.10). Companies that manufacture force plates suitable for equine use include Advanced Medical Technology (AMTI, Watertown, MA), Bertec Corporation (Columbus, OH), and Kistler Instruments Corp. (Amherst, NY).

Installation and calibration of the force plate are critically important to the quality of the data collected. The plate is embedded in a concrete pit to isolate it from surrounding vibrations. The supporting surface must be absolutely level to avoid cross talk between the vertical and horizontal channels. Before recording data, the calibration should be checked by placing a known weight, that is similar in magnitude to the loads that will be applied during normal use, at different locations on the force plate. The same vertical force should be recorded independent of the location, and the position indicated by the force plate should match the actual location of the load.

Data collection

GRFs vary with speed (McLaughlin *et al.*, 1996). Provided the horse's velocity over the force plate is maintained within a narrow range, the GRFs are consistent and repeatable between strides, with analysis of 5 strides being sufficient to provide representative data (Merkens *et al.*, 1986). The horse's average velocity over the plate can be checked using timing lights to record the time taken to cover a known distance as the horse moves over the force plate; data from runs that fall outside the required time range are discarded. Sensors for a simple infrared timing device can be purchased inexpensively. Alternatively, the average horizontal velocity of a marker on the horse during the stride can be determined when the data are analyzed, with strides that fall outside a certain range being discarded. It is sometimes useful to

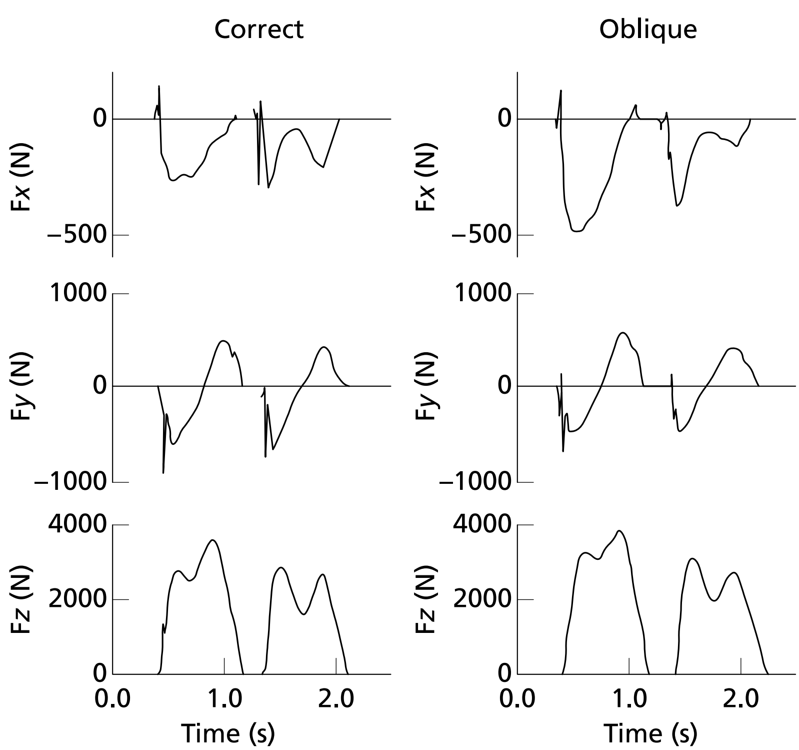

Fig. 3.10 Effect of cross talk due to oblique movement of the horse across the force plate. The transverse (F*x*), longitudinal (F*y*) and vertical (F*z*) ground reaction forces were obtained from the hindlimb of a horse as it walked across the force plate perpendicular to its long axis (graphs on left) or obliquely (graphs on right). (Reprinted with permission from Schamhardt, H.C. (1996) In: *Measuring movement and locomotion: From invertebrates to humans*.)

screen strides in this manner before performing a more detailed analysis.

Bad runs occur when the horse fails to strike the force plate, when the hoof contacts the edge of the plate, or when more than one hoof is on the plate simultaneously. These problems are recognized by the force traces having an unusual shape or magnitude, or failing to return to the baseline between individual limb contacts. It may be helpful to have a video camera focussed on the surface of the force plate to verify the limb placements on its surface.

Normalization

GRFs vary with the body mass of the horse (Barr *et al.*, 1995). Comparisons between horses are facilitated by normalizing the force traces to the horse's weight, so they are expressed in Newtons/kilogram body weight (N/kg). GRFs may also be normalized to the duration of the stance phase, which allows the timing of specific events to be expressed as a percentage of the stance duration.

Standard GRF patterns have been developed for Dutch warmbloods at a walk (Merkens *et al.*, 1988), trot (Merkens *et al.*, 1993a) and canter (Merkens *et al.*, 1993b). Adaptation to other breeds could be accomplished by incorporating appropriate parameters and weighting factors into the formulae used to develop the standard patterns.

Data

Figure 3.11 shows the force patterns of the three force components (vertical, longitudinal, transverse) during the stance phase of a forelimb at a walk and trot. The vertical force, which represents the support function of the limb, has a magnitude of the order of 60% of body weight at the walk and 90% of body weight at a moderate speed trot. In the walk the vertical force trace may be biphasic. If this is the case, the second peak is higher in the forelimbs, the first peak is higher in the hindlimbs. In the trot sharp spikes usually occur immediately after initial ground contact during the period of impulsive loading (impact phase). The trace then rises smoothly to peak when the limb is at its midstance position which is marked by the cannon segment being vertical, after which it decreases to lift off. For both the walk and trot, in the early part of the stance phase the longitudinal force brakes (decelerates) the horse's forward movement as a result of friction that prevents the hoof slipping forward. Later in the stance phase, it changes to a propulsive (accelerating) force (Fig. 3.11). The direction of the horse's motion across the force plate determines whether acceleration or deceleration is recorded as positive. Software correction is applied to standardize the sign convention. The peak value of the longitudinal force is 10–15% of the horse's body weight at the walk and trot, with marked spiking occurring during the impact phase at the trot. The transverse force is much smaller in magnitude, of the order of 2% body weight at the trot. The left to right values recorded by the force plate are converted to represent medial and lateral values for each limb. The center of pressure is located under the middle of the hoof during most of the stance phase, moving rapidly toward the toe at the start of breakover.

Values representing the peak forces and their times of occurrence are extracted from the force tracings. The impulses are determined by time integration of the force curves. A procedure that combined over 90 numbers describing the peak amplitudes, their times of occurrence, and the impulses has been described as the H(orse)INDEX (Schamhardt & Merkens, 1987). This method is valid but has some drawbacks in that the variables used to calculate the index are selected by the user and are essentially dependent on the shape of the signal. Moreover, it does not take account of the real pattern of the curve, which can be accomplished by different techniques that are more suitable for comparing curve patterns.

The stance durations, GRF amplitudes and impulses are symmetrical in sound horses at the walk (Merkens *et al.*, 1986, 1988) and trot (Seeherman *et al.*, 1987; Merkens *et al.*, 1993a). Evaluations of a variety of lamenesses have shown a similar pattern of changes in the GRF, consisting of a reduction in the horizontal decelerating force and reductions in the vertical force amplitude and impulse in a lame forelimb, with compensatory changes in the compensating forelimb. Lameness models that produce these changes include pressure on the hoof sole (Merkens & Schamhardt, 1988); collagenase-induced tendinitis in the flexor tendons or desmitis of the suspensory ligament (Keg *et al.*, 1992); and surgical creation of a full thickness cartilage defect on the radial carpal bone (Morris & Seeherman, 1987). In addition to its value for detecting lameness, the force plate is a sensitive tool for measuring the response of lame horses to diagnostic anesthesia (Keg *et al.*, 1992) or to therapeutic intervention (Gingerich *et al.*, 1979), and for detecting abnormalities in postural sway in horses with neurological diseases (Clayton *et al.*, in press).

Strain Gauges

Body tissues deform in response to an applied load. When a tensile force is applied to a solid material, it causes the length to increase, whereas a compressive force causes the length to decrease. A bending force causes both increases and decreases in length in differ-

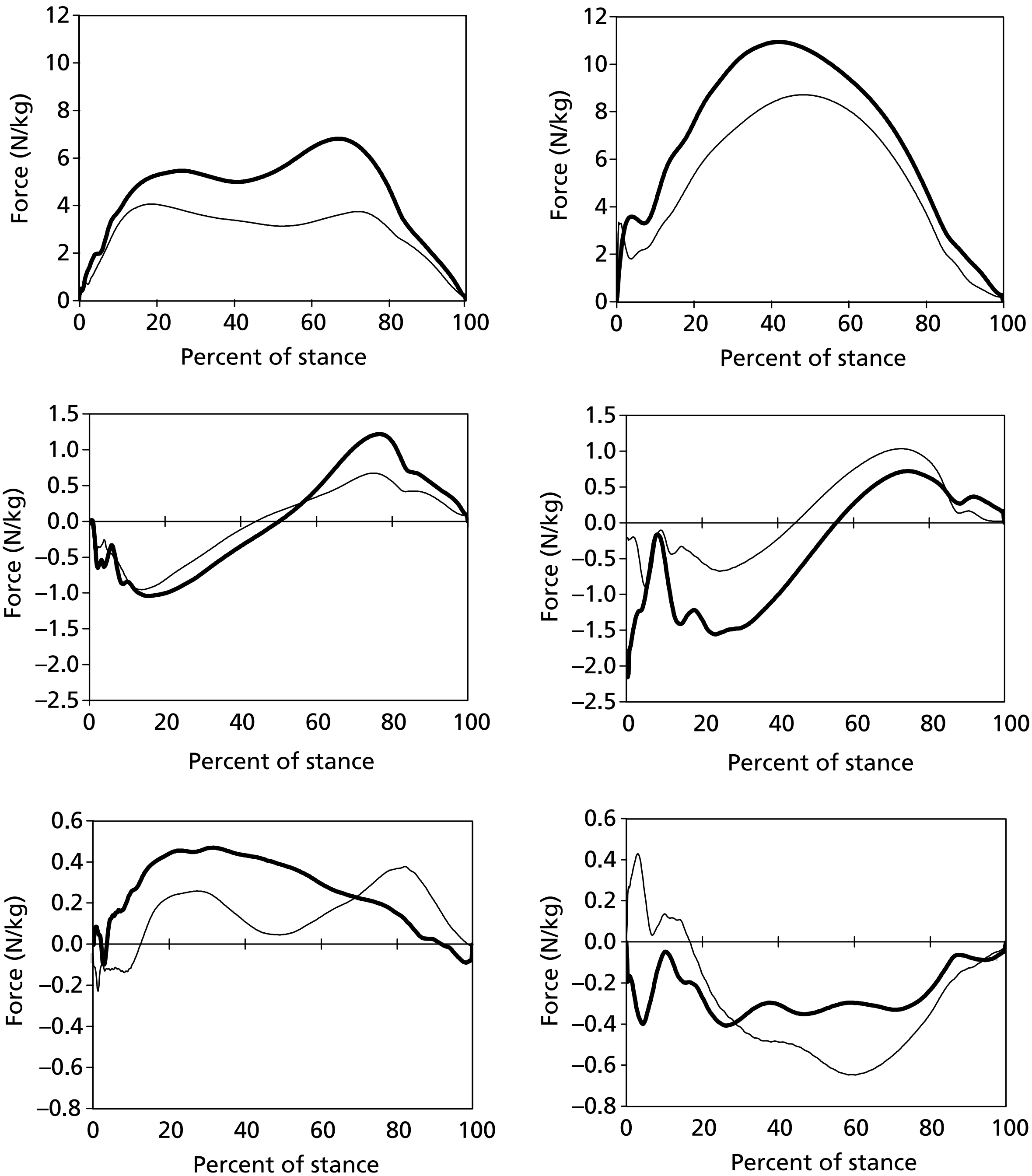

Fig. 3.11 Vertical (top), longitudinal (center) and transverse (bottom) components of the ground reaction force for a horse at the walk (left) and at the trot (right). For the longitudinal force the cranial direction is positive and for the transverse force the medial direction is positive. Forelimb (——). Hind limb (—).

ent parts of the tissue. In ideally elastic materials, the deformation is proportional to the applied force and the material restores its original shape as soon as the deforming force is removed. The deformation of the material, usually expressed in terms of *strain* (ε), is defined as:

$$\varepsilon = \frac{l_1 - l_0}{l_0}$$

where l_0 is the original (or resting) length, l_1 is the length after deformation, and $l_1 - l_1$ represents the change in length. Usually, the resting length is defined as the length at zero loading force. Because strain is a relative measure, it has no units. It is expressed as a fraction or as a percentage strain.

A strain gauge changes its electrical resistance in response to deformation in a certain direction; the change in resistance is converted to a voltage output that is proportional to the strain and is stored for later processing by a computer. A combination of three strain gauges stacked at 45° angles to each other forms a rosette gauge capable of measuring three dimensional strains. Strain gauges, which are a component of force plates and force shoes, can also be used independently to provide direct strain measurements for body tissues.

Measuring strains in hard tissues

Hard tissues, such as bones, deform slightly in multiple directions as a result of the combined effects of weight bearing, tension in the muscles and tendons, and inertial effects due to acceleration and deceleration of the limb. Rosette (three dimensional) gauges, bonded to a bone surface using a thin layer of cyanoacrylate glue, deform with the surface to provide information about the compressive and tensile forces (Lanyon, 1976). The best sites for attachment of strain gauges to bones are in areas where the bone lies subcutaneously, so soft tissue trauma during surgery is minimized. Attachment of strain gauges requires meticulous preparation of the bone surface. The periosteum is removed and the underlying bone is dried before bonding the strain gauges to the bone using cyanoacrylate adhesive. The wires exit the skin through a separate incision. It is important to shield the wires from movement and trauma, since damage to or loosening of the wires is the most frequent reason for failure of the gauges. During data collection, the gauges deform as if they were part of the bone surface. The resulting electrical signal is amplified and transmitted to a data recorder or computer for storage. Strain gauges have been bonded to equine long bones to investigate bone loading under various conditions (e.g. Hartman *et al.*, 1984; Schamhardt *et al.*, 1985; Davies *et al.*, 1993)

A practical problem in quantifying bone strain is that the resting length of bone is difficult to identify. When the horse is standing quietly with the limb lifted from the ground, the loading may be assumed to be small. However, the effects of muscular contraction cannot be excluded completely, and the influence of gravity may also affect the zero strain determination. Software has been developed to calculate a 'zero-strain compensation' for *in vivo* strain gauge data of horses at the walk, using the assumption that strain is minimal in the middle of the swing phase, when the limb is moving forward with an almost constant velocity (Schamhardt & Hartman, 1982).

Surface strain is a consequence of the forces loading the bone. However, the relationship between surface strain and load is very complicated, especially in non-homogeneous, non-linear, visco-elastic structures such as bones (Rybicki *et al.*, 1974). Roszek *et al.* (1993) presented an elegant technique to quantify the loading forces from a post mortem calibration using multiple strain gauges and known bending and torsional loading forces. Without this kind of calibration, however, bone strain recordings are a valuable, but qualitative, estimate of bone loading.

By using 3 or 4 strain rosettes around the perimeter of a long bone shaft, and combining their output with a knowledge of the bone's geometry, the distribution of principal strains can be determined. It has been shown that the loading pattern of each bone is fairly consistent in different activities, though the peak strain and the strain rate vary with gait and speed (Rybicki *et al.*, 1974). This information has been applied in locating the tension surface of various long bones, which is the surface of choice for the application of bone plates. Strain gauges are easily bonded to the hoof wall to study the functional anatomy of the hoof capsule under a variety of loading conditions (Thomasom *et al.*, 1992).

Measuring strains in tendons and ligaments

The long tendons in the lower limb of the horse can be considered as elastic, more or less homogeneous cables. When loaded, their length increases. However, strain in tendons is not as well defined as in bones. An unloaded tendon shrinks in length and the tendon fibers become wrinkled. When elongated, the crimp in the fibers is first straightened out, then the fibers are stretched elastically up to a point, beyond which permanent elongation occurs.

In tendons and ligaments, unidirectional strain gauges are adequate to record tensile strains during loading. The load elongation curve for a tendon has a 'toe' region, which is characterized by having a large elongation for a small load. This region represents straightening of the crimp in the collagen fibers. As loading increases beyond the 'toe' region, there is a linear relationship between load and elongation in the elastic region until the yield point, which occurs around 10–12% strain. Beyond the yield point permanent elongation results as the tendon fibers begin to rupture. A problem in measuring tendon strain lies in defining the initial length of the tendon and the position of zero load, which affects the magnitude of the strains recorded throughout the physiological range. It appears that the resting length, or the length at zero force, can only be approximated. Studies that rely on different criteria for defining zero load give very different strain values during similar activities and at the yield point. An objective method of determining the transition between the toe and the elastic region has been described (Riemersma & Bogert, 1993). Figure 3.12 shows the strain pattern in the suspensory ligament during walking.

Several types of strain gauges have been used to study tendon strains in horses. In a buckle transducer, the tendon is wound over a buckle and preloaded it as it passes over the middle support bar. Tensile loading straightens the tendon and loads the buckle, and this loading is detected by a strain gauge. Calibration of a buckle strain gauge requires transection of the tendon and application of known weights, which limits the use of this type of transducer to a research setting. Another problem with the buckle transducer is that, by forcing the tendon to follow a curved course, its initial strain and tension are altered.

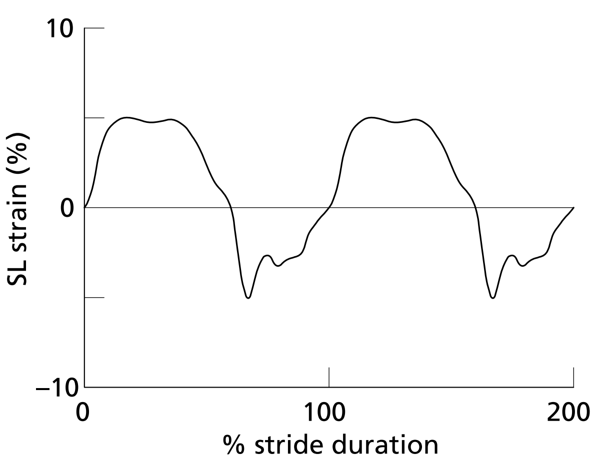

Fig. 3.12 Strain pattern in the suspensory ligament of a walking horse measured using a liquid metal filled strain gauge implanted into the ligament. The stride starts and ends at ground contact of the instrumented limb, which occurs at times 0%, 100% and 200%. (Reprinted with permission from Schamhardt, H.C. (1996) In: *Measuring movement and locomotion: From invertebrates to humans*.)

Liquid metal (e.g. mercury in silastic) strain gauges have the advantage of being calibrated *in vivo*, but they have to be custom made, which is a tricky process. Micro damage in the area of implantation alters the tensile properties of the tendon within a few days after implantation, so readings must be taken as soon as possible after surgery (Jansen *et al.*, 1998). Liquid metal strain gauges have been used to investigate the load distribution between the flexor tendons and suspensory ligament (Jansen *et al.*, 1993), and to detect changes in the loading pattern in response to changes in surface type or shoeing adaptations (Riemersma *et al.*, 1996a, 1996b).

A transducer based on the Hall effect, in which the voltage output of a semiconductor is proportional to the strength of a magnetic field, was used to measure strain in the superficial digital flexor tendon. Although the strains recorded were higher than would be expected, this may have been due to the definition of initial length as the length at heel strike (Stephens *et al.*, 1989).

A novel type of force transducer that detects the strain from a very small part of the tendon has been applied in horses (Platt *et al.*, 1994). A drawback to this type of transducer is that it samples a very small area that is not necessarily representative of strain in the entire tendon.

Accelerometers

Accelerometers measure acceleration of the surface to which they are attached. In equine studies they have most often been applied to the hoof wall, where they are used to detect initial ground contact and to measure the associated acceleration. A hoof-mounted accelerometer is probably the most effective means of measuring certain characteristics of the footing (Barrey *et al.*, 1991) and the efficiency of shock absorbing shoes and pads (Benoit *et al.*, 1991). By mounting accelerometers to the hoof wall and to the bones of the digit, Lanovaz *et al.* (1998) studied the attenuation of impact shock in the distal digit *in vitro*; Willemen (1998) performed simiar measurements both *in vitro* and *in vivo*.

In another application, two accelerometers were secured beneath the horse's sternum to measure longitudinal and dorsoventral accelerations of the trunk segment (Barrey *et al.*, 1994). The data were transmitted telemetrically to a receiver connected to a portable computer. Analysis of the left/right symmetry of the trunk acceleration patterns during trotting detected subtle asymmetries in lame horses (Barrey & Desbrosse, 1996). The same device has been used to study the accelerations of the trunk during jumping (Barrey & Galloux, 1997).

Accelerometers attached to the saddle have been used to measure the acceleration at different gaits and the findings have been applied in the development of a mechanical horse that simulates the motions during walking, trotting, cantering and jumping (Galloux *et al.*, 1994).

TREADMILL EVALUATION

The treadmill is extremely useful for equine gait analysis because the speed of movement is controlled, allowing the horse's gait to be evaluated at the same speed under different circumstances. Theoretically, treadmill locomotion does not differ from overground locomotion (Ingen Schenau, 1980), but differences in kinematic stride variables have been reported (Fredricson *et al.*, 1983; Barrey *et al.*, 1993; Buchner *et al.*, 1994b).

A period of habituation is required before horses move consistently on the treadmill, with habituation occurring more rapidly at faster gaits. Rapid adaptation is seen during the first few training sessions, and by the end of the third 5 min session, the kinematics of the trot have stabilized (Figure 3.13), whereas the walk kinematics are not fully adapted even at the tenth session (Buchner *et al.*, 1994a). During the first session and, to a lesser extent at the start of subsequent sessions, the initial steps are short and quick, with the withers and hind quarters lowered, and the feet splayed to the side to give the horse a larger base of support. Even horses that are experienced on the treadmill take at least one minute for their gait pattern to stabilize each time the belt starts moving (Buchner *et al.*, 1994a).

Comparisons between overground and treadmill locomotion in horses trotting at the same speed under both conditions have shown that speed on the treadmill is achieved with a higher stride frequency and a longer stride length (Barrey *et al.*, 1993). On the treadmill there is an increase in stance duration, earlier placement of the forelimbs, greater retraction of both fore and hindlimbs and reduced vertical excursions of the hooves and the withers (Buchner *et al.*, 1994b).

Horses moving on a treadmill use less energy than horses moving overground at the same speed, which may be partly due to a power transfer from the treadmill to the horse. Although the speed of the treadmill belt is assumed to be constant, in fact it is reduced by about 9% during the first part of the stance phase due to the frictional effect of the vertical force component and the decelerating effect of the longitudinal force component exerted by the horse's limb. In the later part of the stance phase the frictional effect of the vertical force declines while the propulsive longitudinal force tends to accelerate the belt (Schamhardt *et al.*, 1994).

Although the kinematics and energetics of treadmill locomotion are not exactly equivalent to overground locomotion, this does not diminish its value for clinical and research studies involving comparisons between treadmill locomotion under different conditions. Videographic analysis of a horse moving on a treadmill is particularly useful for evaluating hoof balance and the flight arc of the hoof: even without a gait analysis system the tapes can be viewed at normal speed and in slow motion to visualize events that happen too rapidly to be perceived by the human eye.

Kinematic analysis of horses moving on a treadmill has been used to study the movements of the limbs (Back *et*

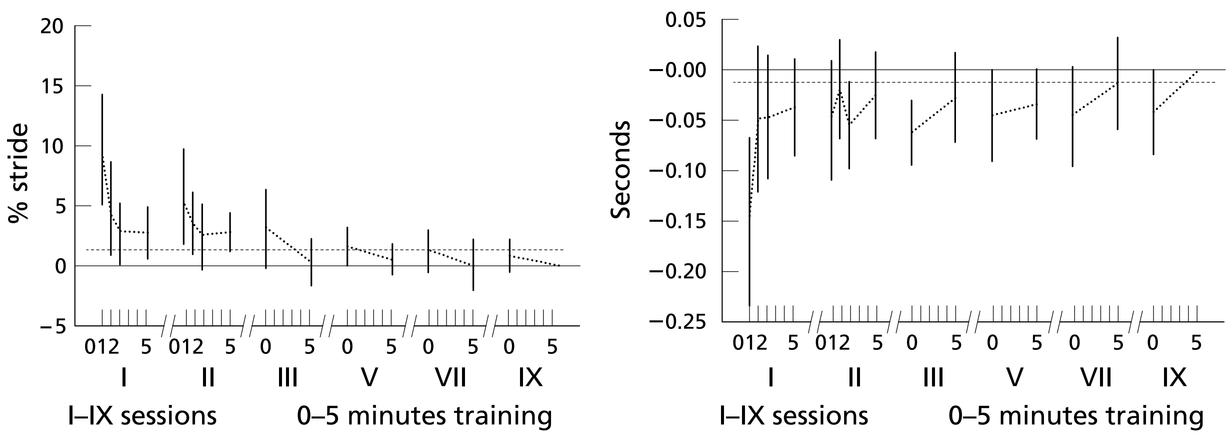

Fig. 3.13 Habituation to treadmill locomotion in 10 horses determined by changes in hindlimb stance duration (expressed as a percentage of stride duration). The horizontal axis shows the number of training sessions, each of 5 min duration. The vertical axis shows the relative stance duration. Reductions in stance duration are regarded as a sign of habituation. The horizontal line indicates the 'habituation limit' based on data of the final recording session. (Reprinted with permission from Buchner *et al*. (1994) *Equine vet. J.* **17**(Suppl.): 13–15.)

al., 1995a, 1995b), ontogeny of the trot (Back *et al.*, 1994), the response to training (Weeren *et al.*, 1993; Corley & Goodship, 1994), the development of gait asymmetries (Drevemo *et al.*, 1987) and adaptations used by the horse to manage lameness (Peloso *et al.*, 1993; Buchner *et al.*, 1995, 1996b, 1996c).

At the University of Zurich, a force plate suitable for equine use has been embedded in a treadmill to measure the vertical forces of all four limbs over an unlimited number of steps at any gait (Weishaupt *et al.*, 1996). The force measuring system consists of 16 piezoelectric force transducers mounted between the treadmill frame and the supporting steel plate over which the belt moves. Each transducer measures the vertical force at the corresponding bearing of the supporting plate. Transfer coefficients have been determined for each of the 16 transducers for each square centimeter of the treadmill surface by the application of a test force. These values are shown as a table that is used in the calculation procedures. The coordinates of each hoof on the treadmill surface are calculated by triangulation based on angle values derived from two electrogoniometers. For each sampling instant, a set of 16 linear equations can be formulated containing the four unknown hoof forces, the four X-Y coordinates of the hoof force application, their corresponding transfer coefficients and the 16 forces from the sensors, from which the individual hoof forces are extracted.

ELECTROMYOGRAPHY

Muscular contraction generates forces that stabilize and move the limbs. Muscle contraction is preceded by electrical activation, which can be detected and recorded as the electromyogram. Electromyography (EMG) gives information on the state of activity of the motor neurones at rest, during reflex contraction and during voluntary contraction. Since it is relatively non-invasive, EMG can be performed on the conscious horse, and can be used during locomotion (Korsgaard, 1982; Tokuriki *et al.*, 1989; Jansen *et al.*, 1992; Tokuriki & Aoki, 1995). The recognition of new neurologic disorders, such as equine motor neurone disease (EMND), hyperkalemic periodic paralysis, myotonia congenita and equine myotonic dystrophy, has resulted in EMG becoming a useful diagnostic tool. However, the characteristic features of neuromuscular disease may be difficult to detect and evaluate without sedation or anesthesia.

The nerve impulse

EMG studies the functional unit of the muscle, the motor unit, which consists of the motor neurone and the muscle fibers it innervates. A resting muscle fiber has a 90 mV potential difference across its surface membrane, with the outer side being positive. During excitation the resting potential is temporarily reversed to 40 mV, with the outside being negative. As the action potential travels along the muscle fiber, the small electrical potential generated across the surface membrane is dissipated in the surrounding interstitial fluid, which is a good electrical conductor. The summation of the electrical changes in the interstitial fluid is recorded as the EMG.

The number of muscle fibers per motor unit is inversely related to the precision of movements. Muscles that direct very precise movements have motor units composed of a small number of muscle fibers, whereas muscles that are primarily concerned with force production can have thousands of muscle fibers innervated by a single motor neurone. The force of muscular contraction is regulated by adjusting the number of motor units that are activated and/or the firing rate of the motor neurones. These factors interact to produce smooth and graded muscle contraction.

EMG equipment

The essential components of an EMG system are electrodes for recording potentials, an amplifier to enlarge the small electric potentials, a filter to reduce unwanted noise, and a data recording device. Data are transferred from the electrodes to the amplifier through wires (Denoix, 1989; Jansen *et al.*, 1992) or via telemetry (Aoki *et al.*, 1984; Tokuriki *et al.*, 1989).

The electrodes function as the antenna to pick up the electrical signal. They may be placed on the skin surface, inserted percutaneously into the muscle or implanted surgically. Surface electrodes have the advantage of being non-invasive but they provide only a gross estimation of muscle activity in the large superficial muscle groups. Jansen *et al.* (1992) found surface electromyography to be a reliable and reproducible technique. However, many locomotor muscles of the horse are deeply placed or lie beneath the thick cutaneous muscles, making them unsuitable for study by surface electrodes. The percutaneous technique involves using a hypodermic needle to introduce fine wires into the muscle belly. Barbed ends usually hold the wires in place. This simple technique does not damage the muscle tissue, but has the disadvantage that the position of the electrodes cannot be visualized directly. Surgical implantation is a more complex, time-consuming and potentially damaging procedure, but it provides the best results in terms of electrical and mechanical reliability, since the operator has direct visual control of the position of the electrodes.

Several electrode configurations are used. A unipolar electrode usually has a single strand of wire coated with an insulating material except for a small length at its distal end. The wire is inserted percutaneously through a small hypodermic needle and the end of the wire is bent back on itself to act as a barb. The potential is measured between the uninsulated tip of the wire and a reference electrode on the skin. Unipolar electrodes detect the time of activation of the muscle, rather than the amplitude of the contraction. Bipolar electrodes measure the voltage difference between two electrical contacts. A simple bipolar design has two hooked wires inserted through a hypodermic needle. Another type is the concentric bipolar electrode, which measures the potential difference between a point-like recording contact and an average of all the potentials in a ring surrounding it at some fixed distance. The advantages of this configuration are that the recording electrode is shielded by the outer needle from electromagnetic noise and the reference is kept as close to the electrode as possible.

The muscle potentials may be displayed on a cathode ray oscilloscope using the convention that a positive potentials is indicated by a downward deflection. A chart recorder may be used to produce a hard copy of the output. The data are usually converted from analog to digital format and stored in a computer. Special software is used to process the information, to measure variables such as the amplitude and frequency of the spikes, to rectify the output, to construct an envelope that touches the peaks of the spikes and to measure the areas under the resulting curves.

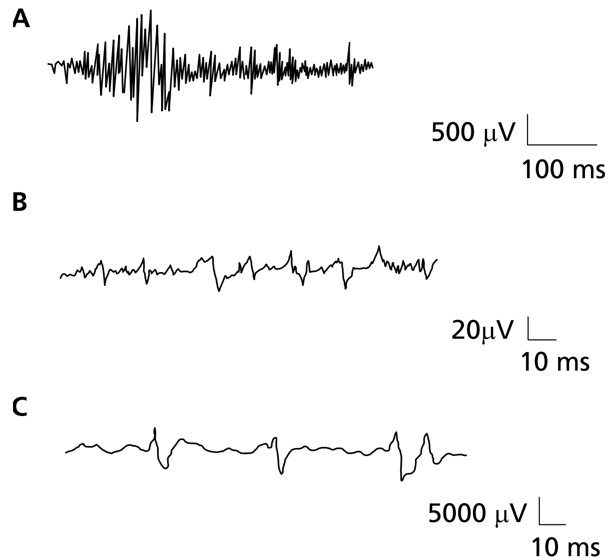

Fig. 3.14 Normal electromyographic findings. **A:** Insertional activity; **B:** endplate noise; **C:** motor unit action potential (MUAP). (Reprinted with permission from Wessum, R. van, Sloet, M.M. & Clayton, H.M. (1999) *Vet. Quart*. **21:** 3–7.)

The electromyogram

During EMG examination there are three phases of electrical activity: insertional activity, resting activity and activity during muscle contraction. The mechanical stimulation associated with insertion or movement of the EMG needle precipitates a discharge of potentials that last only a few milliseconds, end abruptly, and are followed by electrical silence (Fig. 3.14). Increased electrical activity lasting more than 10 ms after insertion or moving the needle is abnormal and thought to be due to hyperirritability and instability of the muscle fiber membrane, which is usually a sign of early denervation atrophy, but it is also seen in myotonic disorders and myositis (Kimura, 1984) and in EMND (Podell *et al.*, 1995). Changes in insertional activity and action potentials may be difficult to detect objectively in standing horses.

Positive sharp waves (PSWs) are monophasic, with a short positive phase followed by a longer, very large negative phase (Fig. 3.14). PSWs occur in muscular diseases such as myositis, exertional rhabdomyolysis and EMND.

Fibrillation potentials are the most commonly observed abnormal electromyographic findings. They have a bi-or triphasic waveform with an initial positive potential that is represented by a downward deflection. They are thought to be spontaneous discharges from acetylcholine-hypersensitive denervated muscle fibers. Fibrillation potentials strongly suggest denervation and may be present as early as 4 to 10 days after denervation, though in horses they may not be seen until 2 weeks or longer after denervation. When denervation persists and atrophy commences, the fibrillation potentials decrease in number and amplitude, finally ceasing when the muscle is completely atrophied. Fibrillations were found in 45% of horses with EMND (Podell *et al.*, 1995), and have been reported in draft horses affected by shivers (Cox, 1992). Fasciculations, which are spontaneously contracting motor units that may be visible at gross inspection, often occur in association with fibrillation potentials in EMND (Podell *et al.*, 1995) and in shivers (Cox, 1992).

Relaxed skeletal muscle is electrically silent, and the resulting fairly flat trace is the baseline electromyogram. When the electrode is positioned near an endplate or nerve twig it gives rise to endplate noise (Fig. 3.14) and endplate spikes, which are usually eliminated by repositioning the needle.

Motor unit action potentials (MUAPs) are the summation of muscle action potentials from the voluntary or reflex contraction of myofibers in a motor unit. Approximately 50 muscle fibers around a needle electrode contribute to the observed potential. Dedicated software is used to measure the amplitude and frequency of the MUAPs, rectify the curves, construct envelopes and calculate the area under the curves.

Polyphasic MUAPs are potentials during submaximal muscle contraction that have more than four phases and a decreased amplitude and duration. These are indicative of a diffuse loss of muscle fibers resulting in the need for extra motor unit stimulation in order to perform the work normally done by fewer motor units, as in primary myopathies (Andrews & Fenner, 1987).

Myotonic discharges are the result of repeated spontaneous electrical discharges of individual myofibers or groups of myofibers, not followed by a muscle contraction. Myotonic discharges have a long duration of 4 to 5s, and their amplitude waxes and wanes during the discharge. In the horse myotonic discharges occur in myotonic dystrophy (Hegreberg *et al.*, 1990), hyperkalemic periodic paralysis (Naylor *et al.*, 1992) and Australian stringhalt (Huntington *et al.*, 1989).

Studies of athletic horses have described the activation pattern of various muscles during normal locomotion (Wentink, 1978; Korsgaard, 1982; Tokuriki *et al.*, 1989). On the basis of EMG activity, muscles were shown to be active at times that were different from expectations based on their topography (Wentink, 1978). This work led to an appreciation of the importance of muscles for stabilizing the joints rather than simply acting as prime movers. Recent studies describing the net joint moments at different joints and the work done across these joints is shedding new light on the interpretation of EMG findings (Colborne *et al.*, 1998; Clayton *et al.*, 1998; Lanovaz *et al.*, 1999).

The amplitude of the EMG signal depends on the dimensions of the electrodes, their electrical contact with the muscle, and the kind of electrodes: signals from indwelling wire electrodes usually are much lower than those obtained from surface electrodes. However, the major influence on the EMG signal amplitude is caused by the degree of activation of the muscle. When the muscle is completely activated, the EMG signal will reach a maximum. This relationship allows the EMG signal amplitude to be used as a measure of the degree of activation, and thus indirectly, of the muscle force development (Hof, 1984). However, it is not possible to determine a reliable estimate of muscle force development on the basis of EMG signal analysis alone. This requires the development of a sophisticated muscle model that incorporates the muscle architecture, the force–length and force–velocity relationships of the muscle fibers, and the activation of the muscle (possibly from EMG signal analysis).

ARTIFICIAL NEURAL NETWORKS

Artificial neural networks (ANN) are computer programs consisting of cells that are organized in analogy with the architecture of the human brain. They can be used for qualitative and quantitative pattern recognition. ANNs are trained using a set of input data that are provided together with a target output. Training sessions are repeated until the ANN 'learns' to interpret the input data to produce an appropriate output. For example, in training an ANN for lameness diagnosis, input might be in the form of kinematic data, while the target output is the clinical diagnosis.

Preliminary studies have indicated that the GRF may be estimated from hoof wall strain using as few as two gauges, one at the toe and one on the lateral hoof wall. Since the relationship between hoof wall strain and GRF is non-linear, common analytical tools are not applicable. ANNs, however, excel in performing this type of complex pattern recognition task (Savelberg *et al.*, 1997). They have also shown the ability to detect the lame limb and to assess the lameness degree with reasonable accuracy if adequate data were used to train the ANN (Savelberg *et al.*, 1997; Schlobesberger, 1996).

REFERENCES

Adrian, M., Grant, B., Ratzlaff, M., Ray, J. and Boulton, C. (1977) Electrogoniometric analysis of equine metacarpophalangeal joint lameness. *Am. J. Vet. Res.* **38**: 431.

Andrews, F.M. and Fenner, W.R. (1987) Indications and use of electrodiagnostic aids in neurologic disease. *Vet. Clin. North Am.: Equine Pract.* **3**: 293–322.

Aoki, O., Tokuriki, M., Kurakawa, Y., Masaaki, M. and Kita, T. (1984) Electromyographic studies on supraspinatus and infraspinatus muscles of the horse with or without a rider in walk, trot and canter. *Bull. Equine Res. Inst.* **21**: 100–104.

Back, W., Barneveld, A., Schamhardt, H.C., Bruin, G. and Hartman, W. (1994) Longitudinal development of the kinematics of 4-, 10-, 18-and 26-month-old Dutch Warmblood horses. *Equine Vet. J.* **17**(Suppl.): 3–6.

Back, W., Barneveld, A., Weeren, P.R. and van den Bogert, A.J. (1993) Kinematic gait analysis in equine carpal lameness. *Acta Anat.* **146**: 86–89.

Back, W., Schamhardt, H.C., Savelberg, H.C.C.M., Bogert, A.J., van den, Bruin, G., Hartman, W. and Barneveld, A. (1995a) How the horse moves. 1. Significance of graphical representations of equine forelimb kinematics. *Equine Vet. J.* **27**: 31–38.

Back, W., Schamhardt, H.C., Savelberg, H.C.C.M., Bogert, A.J., van den, Bruin, G., Hartman, W. and Barneveld, A. (1995b) How the horse moves. 2. Significance of graphical representations of equine hindlimb kinematics. *Equine Vet. J.* **27**: 39–45.

Barr, A.R.S., Dow, S.M. and Goodship, A.E. (1995) Parameters of forelimb ground reaction forces in 48 normal ponies. *Vet. Rec.* **136**: 283–286.

Barrey, E. (1990) Investigation of the vertical hoof force distribution in the equine forelimb with an instrumented horseboot. *Equine Vet. J.* **9**(Suppl.): 35–38.

Barrey, E. and Desbrosse, F. (1996) Lameness detection using an accelerometric device. *Pferdeheilkunde* **12**: 617–622.

Barrey, E. and Galloux, P. (1997) Analysis of the equine jumping technique by accelerometry. *Equine Vet. J.* **23**(Suppl.): 45–49.

Barrey, E., Galloux, P., Valette, J.P., Auvinet, B. and Wolter, R. (1993) Stride characteristics of overground versus treadmill locomotion. *Acta Anat.* **146**: 90–94.

Barrey, E., Hermelin, M., Vaudelin, J.L., Poirel, D. and Valette, P. (1994) Utilisation of an accelerometric device in equine gait analysis. *Equine Vet. J.* **17**(Suppl.): 7–12.

Barrey, E., Landjerit, B and Wolter, R. (1991) Shock and vibration during hoof impact on different track surfaces. *Equine Exerc. Physio.* **3**: 97–106.

Benoit, P., Barrey, E., Regnault, J.C. and Brochet, J.L. (1991) Comparison of the damping effect of different shoeing by the measurement of hoof acceleration. *Acta Anat.* **146**: 109–113.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C. *et al.* (1994a) Habituation of horses to treadmill locomotion. *Equine Vet. J.* **17**(Suppl.): 13–15.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C. *et al.* (1994b) Kinematics of treadmill versus overground locomotion in horses. *Vet. Quart.* **16**(Suppl. 2): S87–90.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C. *et al.* (1995) Temporal stride patterns in horses with experimentally induced fore or hind limb lameness. *Equine Vet. J.* **18**(Suppl.): 161–165.

Buchner, H.H.F., Savelberg, H.H.C.M. and Becker, C.K. (1996a) Load redistribution after desmotomy of the accessory ligament of the deep digital flexor tendon in adult horses. *Vet. Quart.* **18**(Suppl. 2): S70–74.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C. *et al.* (1996b) Limb movement adaptations in horses with experimentally induced fore or hind limb lameness. *Equine Vet. J.* **28**: 63–70.

Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C. *et al.* (1996c) Head and trunk movement adaptations in horses with experimentally induced fore or hind limb lameness. *Equine Vet. J.* **28**: 71–76.

Clayton, H.M., Schamhardt, H.C., Lanovaz, J.L., Colborne, G.R. and Willemen, M.A. (1999) Superficial digital flexor tendinitis: 2. Net joint moments and joint powers. *Am. J. Vet. Res.* (in press).

Clayton, H.M., Schott, H.C., Littlefield L and Lanovaz, J.L. (1999) Center of pressure analysis in horses. *Am. Coll. Vet. Int. Med.* (Abstracts; in press).

Colborne, G.R., Lanovaz, J.L., Sprigings, E.J., Schamhardt, H.C. and Clayton, H.M. (1998) Forelimb joint moments and power during the walking stance phase of horses. *Am. J. Vet. Res.* **59**: 609–614.

Corley, J.M. and Goodship, A.E. (1994) Treadmill training induced changes to some kinematic variables measured at the canter in Thoroughbred fillies. *Equine Vet. J.* **17**(Suppl.): 20–24.

Cox, J. (1992) Neuromuscular disorders. In: Mills, L. (ed) *Current Therapy in Equine Medicine*. Philadelphia: W.B. Saunders, pp. 571–573.

Davies, H.M.S., McCarthy, R.N. and Jeffcott, L.B. (1993) Strain in the equine metacarpus during locomotion. *Acta Anat.* **146**: 148–153.

DeLuzio, K.J., Wyss, U.P., Li, J. and Costigan, P.A. (1993) A procedure to validate three dimensional motion assessment systems. *J. Biomech.* **26**: 753–759.

Denoix, J.M. (1989) Biomechanical studies in the athletic horse. Present methods and objectives. *Rec. Med. Vet.* **165**: 107–115.

Drevemo, S., Dalin, G., Fredricson, I. and Hjertén, G. (1980a) Equine locomotion 1: The analysis of linear and temporal stride characteristics of trotting Standardbreds. *Equine Vet. J.* **12**: 60–65.

Drevemo, S., Dalin, G., Fredricson, I. and Björne, K. (1980b) Equine locomotion 3: The reproducibility of gait in Standardbred trotters. *Equine Vet. J.* **12**: 71–73.

Drevemo, S., Fredricson, I. and Hjertén, G. (1987) Early development of gait asymmetries in trotting Standardbred colts. *Equine Vet. J.* **19**: 189–191.

Fioretti, S. and Jetto, L. (1989) Accurate derivative estimation from noisy data: a state-space approach. *Int. J. Systems Sci.* **20**: 33–53.

Frederick, F.H. Jr and Henderson, J.M. (1970) Impact force measurement using preloaded transducers. *Am. J. Vet. Res.* **31**: 2279–2283.

Fredricson, I. and Drevemo, S. (1972) Methodological aspects of kinematics of the joints in the forelimbs of fast moving horses. *Acta Vet. Scand.* **37**: 93–136.

Fredricson, I., Drevemo, S., Dalin, G., Hjertén, G., Björne, K., Rynde, R. and Franzén, G. (1983) Treadmill for equine locomotion analysis. *Equine Vet. J.* **15**: 111–115.

Galloux, P., Richard, N., Dronka, T. *et al.* (1994) Analysis of equine gait using three dimensional accelerometers fixed on the saddle. *Equine Vet. J.* **17**(Suppl.): 44–47.

Gingerich, D.A., Auer, J.A., Fackelman, G.E. (1979) Force plate studies on the effect of exogenous hyaluronic acid on joint function in equine arthritis. *J. Vet. Pharmacol. Therap.* **2**: 291–298.

Grood, E.S. and Suntay, W.J. (1983) A joint coordinate system for the clinical description of three dimensional motions: applications to the knee. *J. Biomech. Eng.* **105**: 136–144.

Hartman, W., Schamhardt, H.C., Lammertink, J.L.M.A. and Badoux, D.M. (1984) Bone strain in the equine tibia: An in vivo strain gauge analysis. *Am. J. Vet. Res.* **45**: 880–884.

Hegreberg, G.A. and Reed, S.M. (1990) Skeletal muscle changes associated with equine myotonic dystrophy. *Acta Neuropathol.* **80**: 426–431.

Hjertén, G. and Drevemo, S. (1987) A method to analyze forces and moments in the extremities of the horse during the stance phase at the trot. *Equine Exerc. Physiol.* **2**: 587–598.

Hof, A.L. (1984) EMG and muscle force: an introduction. *Human Movement Sci.* **3**: 119–153.

Huntington, P.J., Jeffcott, L.B., Friend, S.C.E., Luff, A.R., Finkelstein, D.I. and Flynn, R.J. (1989) Australian stringhalt-epidemiological, clinical and neurological investigations. *Equine Vet. J.* **21**: 266–273.

Ingen Schenau, G.J. van (1980) Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. *Med. Sci. Sports Exerc.* **12**: 257–261.

Jansen, M.O., Bogert, A.J. van den and Schamhardt, H.C. (1993) In vivo tendon forces in the forelimb of ponies at the walk, validated by ground reaction force measurements. *Acta Anat.* **146**: 162–167.

Jansen, M.O., Raaij, J.A.G.M. van, Bogert, A.J., van den, Schamhardt, H.C. and Hartman, W. (1992) Quantitative analysis of computer-averaged electromyographic profiles of intrinsic limb muscles in ponies at the walk. *Am. J. Vet. Res.* **53**: 2343–2349.

Jansen, M.O., Schamhardt, H.C., Bogert, A.J. van den and Hartman, W. (1998) Mechanical properties of the tendinous equine interosseus muscle affected by *in vivo* transducer implantation. *J. Biomech.* **31**: 485–490.

Keegan, K.G., Wilson, D.A., Wilson, D.J. *et al.* (1998) Evaluation of mild lameness in horse trotting on a treadmill by clinicians and interns or residents and correlation of their assessments with kinematic gait analysis. *Am. J. Vet. Res.* **59**: 1370–1377.

Keg, P.R., Belt, A.J.M. van den, Merkens, H.W., Barneveld, A. and Dik, K.J. (1992) The effect of regional nerve blocks on the lameness caused by collagenase induced tendonitis in the midmetacarpal region of the horse: a study using gait analysis, and ultrasonography to determine tendon healing. *J. Vet. Med.* **A39**: 349–364.

Kimura, J. (1984) *Electrodiagnosis in Disease of Nerve and Muscle: Principles and Practice*. Philadelphia: F.A. Davis.

Korsgaard, E. (1982) *Muscle function in the forelimb of the horse. An electromyographical and kinesiological study. PhD thesis, Kopenhagen.*

Lanovaz, J.L., Clayton, H.M. and Watson, L.G. (1998) In vitro attenuation of impact shock in equine digits. *Equine Vet. J.* **26**(Suppl.): 96–102.

Lanovaz, J.L., Clayton, H.M., Colborne, G.R. and Schamhardt, H.C. (1999) Forelimb kinematics and joint moments during the swing phase of the trot. *Equine Vet. J.* (in press).

Lanyon, L.E. (1976) The measurement of bone strain in vivo. *Acta Orthop. Belg.* **42**(Suppl. 1): 98–108.

Leach, D.H. and Dyson, S. (1988) Instant centres of rotation of equine limb joints and their relationship to standard skin marker locations. *Equine Vet. J.* **6**(Suppl.): 113–119.

Licka, T. and Peham, C. (1998) An objective method for evaluating the flexibility of the back of standing horses. *Equine Vet. J.* **30**: 412–415.

Linford, R.L. (1994) Camera speeds for optoelectronic assessment of stride-timing characteristics in horses at the trot. *Am. J. Vet. Res.* **55**: 1189–1195.

McLaughlin, R.M., Gaughan, E.M., Roush, K. and Skaggs, C. (1996) Effects of subject velocity on ground reaction force measurements and stance times in clinically normal horses at the walk and trot. *Am. J. Vet. Res.* **57**: 7–11.

Merkens, H.W. and Schamhardt, H.C.C. (1988) Evaluation of equine locomotion during different degrees of experimentally induced lameness 1: Lameness model and quantification of ground reaction force patterns of the limbs. *Equine Vet. J.* **6**(Suppl.): 99–106.

Merkens, H.W., Schamhardt, H.C., Hartman, W. and Kersjes, A.W. (1986) Ground reaction force patterns of Dutch Warmblood horses at normal walk. *Equine Vet. J.* **18**: 207–214.

Merkens, H.W., Schamhardt, H.C., Hartman, W. and Kersjes, A.W. (1988) The use of Horse(INDEX), a method of analysing the ground reaction force patterns of lame and normal gaited horses at the walk. *Equine Vet. J.* **20**: 29–36.

Merkens, H.W., Schamhardt, H.C., Osch, G.J.V.M. and Bogert, A.J. (1993a) Ground reaction force patterns of Dutch Warmblood horses at normal trot. *Equine Vet. J.* **25**: 134–137.

Merkens, H.W., Schamhardt, H.C., Osch, G.J.V.M. van, and Hartman, W. (1993b) Ground reaction force patterns of Dutch Warmbloods at canter. *Am. J. Vet. Res.* **54**: 670–674.

Morris, E.A. and Seeherman, H.J. (1987) Redistribution of ground reaction forces in experimentally induced carpal lameness. *Equine Exerc. Physiol.* **2**: 553–563.

Naylor, J.M., Robinson, J.A., Crichlow, E.C. and Steiss, J.E. (1992) Inheritance of myotonic discharges in american quarter horses and the relationship to hyperkalemic periodic paralysis. *Can. J. Vet. Res.* **56**: 62–66.

Nicodemns, M.C., Lanovaz, J.L., Corn, C. and Clayton, H.M. (1999) The application of virtual markers to a joint coordinate system for equine three dimensional motions. *Proc. Equine Nutr. Physiol. Soc.* **16**: 24–25.

Niki, Y., Ueda, Y., Yoshida, K. and Masumitsu, H. (1982) A force plate study in equine biomechanics. 2. The vertical and fore-aft components of floor reaction forces and motion of equine limbs at walk and trot. *Bull. Equine Res. Inst.* **19**: 1–17.

Peloso, J.G., Stick, J.A., Caron, J.P., Peloso, P.M. and Soutas-Little, R.W. (1993) Computer-assisted three dimensional gait analysis of amphotericin-induced carpal lameness in horses. *Am. J. Vet. Res.* **54**: 1535–1543.

Platt, D., Wilson, A.M., Timbs, A., Wright, I.M. and Goodship, A.E. (1994) Novel force transducer for the measurement of tendon forces in vivo. *J. Biomech.* **27**: 1489–1493.

Podell, M., Valentine, B.A., Cummings, J.F. *et al.* (1995) Electromyography in acquired equine motor neuron disease. *Prog. Vet. Neurol.* **6**: 128–134.

Pratt, G.W. Jr and O'Connor, J.T. Jr (1976) Force plate studies of equine biomechanics. *Am. J. Vet. Res.* **37**: 1251–1255.

Ratzlaff, M.H., Grant, B.D., Adrian, M. and Feeney-Dixon, C. (1979) Evaluation of equine locomotion using electrogoniometry and cinematography: research and clinical applications. *Proc. Am. Assoc. Equine Practnrs.* **25**: 381.

Ratzlaff, M.H., Grant, B.D., Hyde, M.L. and Balch, O.K. (1994) Rupture of the distal sesamoidean ligaments of a horse: vertical forces and temporal components of the strides before, during and after injury. *J. Equine Vet. Sci.* **14**: 45–52.

Ratzlaff, M.H., Hyde, M.L., Grant, B.D., Balch, O. and Wilson, P.D. (1990) Measurement of vertical forces and temporal components of the strides of galloping horses using instrumented shoes. *J. Equine Vet. Sci.* **10**: 23–25.

Riemersma, D.J. and Bogert, A.J. van den (1993) A method to estimate the initial length of equine tendons. *Acta Anat.* **146**: 120–122.

Riemersma, D.J., Bogert, A.J. van den, Jansen, M.O. and Schamhardt, H.C. (1996a) Tendon strain in the forelimbs as a function of gait and ground characteristics, and in vitro limb loading in ponies. *Equine Vet. J.* **28**: 133–138.

Riemersma, D.J., Bogert, A.J. van den, Jansen, M.O. and Schamhardt, H.C. (1996b) Influence of shoeing on ground reaction forces and tendon strains in the forelimbs of ponies. *Equine Vet. J.* **28**: 126–132.

Roepstorff, L. and Drevemo, S. (1993) Concept of a force-measuring horseshoe. *Acta Anat.* **146**: 114–119.

Roepstorff, L., Johnston, C. and Drevemo, S. (1994) The infleunces of different treadmill constructions on ground reaction forces as determined by the use of a force-measuring shoe. *Equine Vet. J.* **17**(Suppl.): 71–74.

Roszek, B., Loon, P. van, Weinans, H. and Huiskes, R. (1993) In vivo measurements of the loading conditions on the tibia of the goat. *Acta Anat.* **146**: 188–192.

Rubin, C.T. and Lanyon, L.E. (1982) Limb mechanics as a function of speed and gait: A study of functional strains in the radius and tibia of horse and dog. *J. Exp. Biol.* **101**: 187–211.

Rybicki, E.F., Simonen, F.A., Mills, E.J. *et al.* (1974) Mathematical and experimental studies on the mechanics of plated transverse fractures. *J. Biomech.* **7**: 377–384.

Savelberg, H.H.C.M., Loon, J.P. van and Schamhardt, H.C. (1997) Ground reaction forces in horses assessed from hoof wall deformation using artificial neural networks. *Equine Vet. J.* **23**(Suppl.): 6–8.

Schamhardt, H.C. (1996) Quantitative analyses of equine locomotion. In: Ossenkopp, K.-P., Kavakiers, M. and Sanberg, P.R. (eds) *Measuring Movement and Locomotion: from Invertebrates to Humans*, pp. 189–211.

Schamhardt, H.C. and Hartman, W. (1982) Automatic zero strain compensation of in vivo bone strain recordings. *J. Biomech.* **15**: 621–624.

Schamhardt, H.C. and Merkens, H.W. (1987) Quantification of equine ground reaction force patterns. *J. Biomech.* **20**: 443–446.

Schamhardt, H.C.C., Bogert, A.J. van den, Lammertink, J.L.M.A. (1994) Power transfer from treadmill engine to athlete. *Proc. Canadian Soc. Biomech.* pp. 306–307.

Schamhardt, H.C., Bogert, A.J. van den, Lammertink, J.L.M.A. and Markies, H. (1992) Measurement and analysis of equine locomotion using a modified CODA-3 kinematic analysis system. *Proc. 8th Mtg. Eur. Soc. Biomech.*, p. 270.

Schamhardt, H.C., Hartman, W. and Lammertink, J.L.M.A. (1985) In vivo bone strain in the equine tibia before and after transection of the peroneus tertius muscle. *Res. Vet. Sci.* **39**: 139–144.

Schamhardt, H.C., Bogert, A.J. van den and Hartman, W. (1993a) measurement techniques in animal locomotion analysis. *Acta Anat.* **146**: 123–129.

Schamhardt, H.C., Merkens, H.W., Vogel, V. and Willekens, C. (1993b) External loads on the limbs of the jumping horse at take-off and landing. *Am. J. Vet. Res.* **54**: 675–680.

Schlosberger, H. (1996) Einsatz eines neuronalen Netzes bei der Lahmheitsuntersuchung von Pferden im Trab. *Dissertation, Wien.*

Schryver, H.F., Bartel, D.L., Langrana, N. and Lowe, J.E. (1978) Locomotion in the horse: Kinematics and external and internal forces in the normal equine digit in the walk and trot. *Am. J. Vet. Res.* **39**: 1728–1733.

Seeherman, H.J., Morris, E.A. and Fackelman, G.E. (1987) Computerized force plate determination of equine weightbearing profiles. *Equine Exerc. Physiol.* **2**: 537–552.

Stephens, P.R., Nunamaker, D.M., Butterweck, D.M. (1989) Application of a Hall-effect transducer for measurement of tendon strain in horses. *Am. J. Vet. Res.* **50**: 1089–1095.

Sustronck, B. (1994) Electromyographic examination in the horse. *Vet. Annual* **34**: 97–106.

Taylor, B.M., Tipton, C.M., Adrian, M. and Karpovich, P.V. (1966) Action of certain joints in the legs of the horse recorded electrogoniometrically. *Am. J. Vet. Res.* **27**: 85–89.

Thomason, J.J., Biewener, A.A. and Bertram, J.E.A. (1992) Surface strains on the equine hoof wall *in vivo*: implications for the material design and functional morphology of the wall. *J. Exp. Biol.* **166**: 145–168.

Tokuriki, M., Aoki, O., Niki, Y., Kurakawa, Y., Hataya, M. and Kita, T. (1989) Electromyographic activity of cubital joint muscles in horses during locomotion. *Am. J. Vet. Res.* **50**: 950–957.

Tokuriki, M. and Aoki, O. (1995) Electromyographic activity of the hindlimb muscles during the walk, trot and canter. *Equine Vet. J.* **18** (Suppl.): 152–155.

Weeren, P.R. van, Bogert, A.J. van den and Barneveld, A. (1990a) A quantitative analysis of skin displacement in the trotting horse. *Equine Vet. J.* **9** (Suppl.): 101–109.

Weeren, P.R. van, Bogert, A.J. van den and Barneveld, A. (1990b) Quantification of skin displacement in the proximal parts of the limbs of the walking horse. *Equine Vet. J.* **9** (Suppl.): 110–118.

Weeren, P.R. van, Bogert, A.J. van den and Barneveld, A. (1992) Correction models for skin displacement in equine kinematic gait analysis. *J. Equine Vet. Sci.* **12**: 178–192.

Weeren, P.R. van, Bogert, A.J. van den, Back, W., Bruin, G. and Barneveld, A. (1993) Kinematics of the Standardbred trotter measured at 6, 7, 8 and 9 m/s on a treadmill, before and after 5 months prerace training. *Acta Anat.* **146**: 154–161.

Weishaupt, M.A., Hogg, H.P., Wiestner, T., Demuth, D.C. and Auer, J.A. (1996) Development of a technique for measuring ground reaction force in the equine on a treadmill. *Abstr. 3rd Int. Conf. Equine Locomotion*, Saumur, France.

Wentink, G.H. (1978) Biokinetical analysis of the movements of the pelvic limb of the horse and the role of the muscles in the walk and trot. *Anat. Embryol.* **152**: 261–272.

Willemen, M.A., Jacobs, M.W.H. and Schamhardt, H.C. (1997) In vitro transmission and attenuation of impact vibrations in the lower forelimb of the horse. In: Willemen, M.A. (ed) Horseshoeing: a biomechanical analysis. *PhD thesis, Utrecht University.*