4

Kinematics

Rene van Weeren

Introduction

Kinematics is a subdiscipline of mechanics that studies the motions of objects without taking into account the forces that generate this motion. When considering the equine back, one should realise that the back is a segmental, complex structure made up of a large number of separate, but intricately linked rigid bodies, which are the vertebrae. The motion of the thoracolumbar vertebral column is the sum of motions of the individual vertebrae, which are, however, severely restricted in their movement through numerous anatomical constraints such as muscles, ligaments, intervertebral joints and the presence of ribs. In the same way that kinematics of individual vertebrae contribute to back kinematics, back motion can be considered to be one of the constituting elements of the kinematics of the entire body, and hence of the way of moving of the individual. The question of how the back, which bridges the gap between the limbs, functions in quadrupedal locomotion has intrigued scientists for millennia and is an active area of research and discussion today.

In this chapter first an overview is given of the various biomechanical concepts that have been presented as good models for the quadrupedal back. Then, kinematics of the equine back is discussed based on *ex vivo* and *in vivo* research. After that studies are discussed that have applied newly acquired knowledge on equine back kinematics to answer clinical or equestrian questions. The chapter concludes with a brief evaluation of the importance of equine back kinematics in a general sense, and some ideas on the possible use of data on back kinematics for the management of equine health and performance in the future.

Historical Perspective

A scientific interest in the equine gait has existed since horses became an integral part of society and good orthopaedic health was vital for the satisfactory fulfilment of the roles the animal had in agriculture, transport and, most important of all, the military. Technical advances allowed research in equine gait analysis to flourish from the 1870s until the outbreak of World War II, but the rapid loss of all traditional roles of the horse in society caused interest in this kind of research to wane after World War II. However, the comeback of the species as a sports and leisure animal from the mid-1960s led to what has been called the Second Golden Age of equine locomotion research [1]. This Second Golden Age was facilitated by the vast advances in motion capture technology and computational power that simultaneously occurred during this time.

During the Second Golden Age attention focused, during the first decades, principally on limb kinematics and kinetics, with studies on the back being limited to work on cadaver specimens. Only in relatively recent years has

Equine Neck and Back Pathology: Diagnosis and Treatment, Second Edition. Edited by Frances M.D. Henson.

more work on the back been done in the living animal. At present, studies are emerging that use the recently acquired fundamental knowledge of equine back kinematics and newly developed, validated analysis techniques for a variety of more applied studies. These studies try to answer questions with respect to the use and mobility of the back that have importance to both veterinary surgeons and a wider equestrian audience.

Biomechanical Models of How the Equine Back Works

From Roman Times – The 'Architectural' Analogy

Mankind has been thinking about how the mammalian back could best be understood from very earliest times. The famous Roman physician Galen (129–200 AD) described the first known concept [2]. He refers to the prevailing architecture of his days and describes the quadrupedal back as 'a vaulted roof sustained by four pillars', the limbs. The spinous processes, pointing in a caudodorsal direction on the ascending part of the arch (or the anterior thoracic part of the trunk) and in a craniodorsal direction on the descending part (posterior thoracic and lumbar part), with the anticlinal (Chapter 1) vertebra at the top, would prevent the roof from collapsing. Though well thought out, this very first concept cannot be correct because it implies a constant contact between the spinous processes, which is not the case under physiological conditions and in fact may be, if present, a cause of pathology (Chapter 13).

The Nineteenth Century – The 'Bridge' Analogy

The next concept was proposed in the middle of the nineteenth century and was again inspired by the technical advances in engineering of those days. This was a time when the railways started to span continents, crossing rivers and ravines with the help of steel bridges that were masterpieces of daring new construction technology. In the bridge concept of the equine back the limbs are the land abutments of the bridge and the gap between these is spanned by the bridge itself [3–5]. This consists of an upper ledger (the supraspinous ligament), a lower ledger (the vertebral bodies) and a number of smaller girders, pointing in either the craniodorsal or caudodorsal direction (the spinous processes and the interspinous ligaments) (Figure 4.1). The bridge concept dominated the veterinary and zoological literature for a long period and has been further elaborated in order to include the biomechanical influences of the head and the tail by using a wide variety of bridge types (Figure 4.2). Even today the model has its

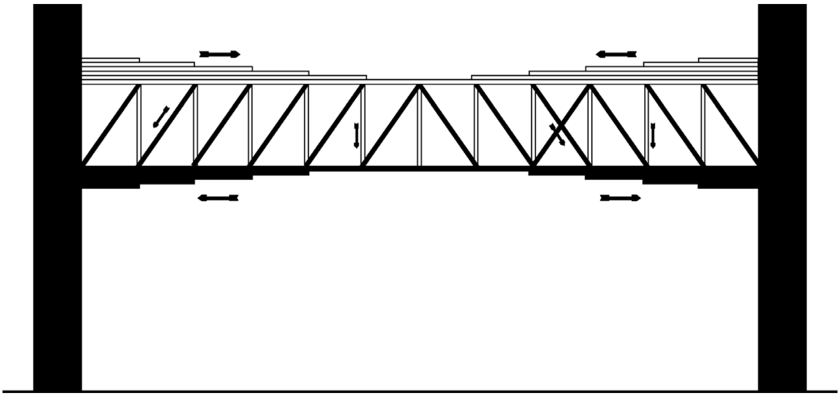

Figure 4.1 A diagram to show the bridge concept of the vertebral column as depicted by Krüger [4]. Closed arrows show compressive forces. *Source:* Adapted from [4].

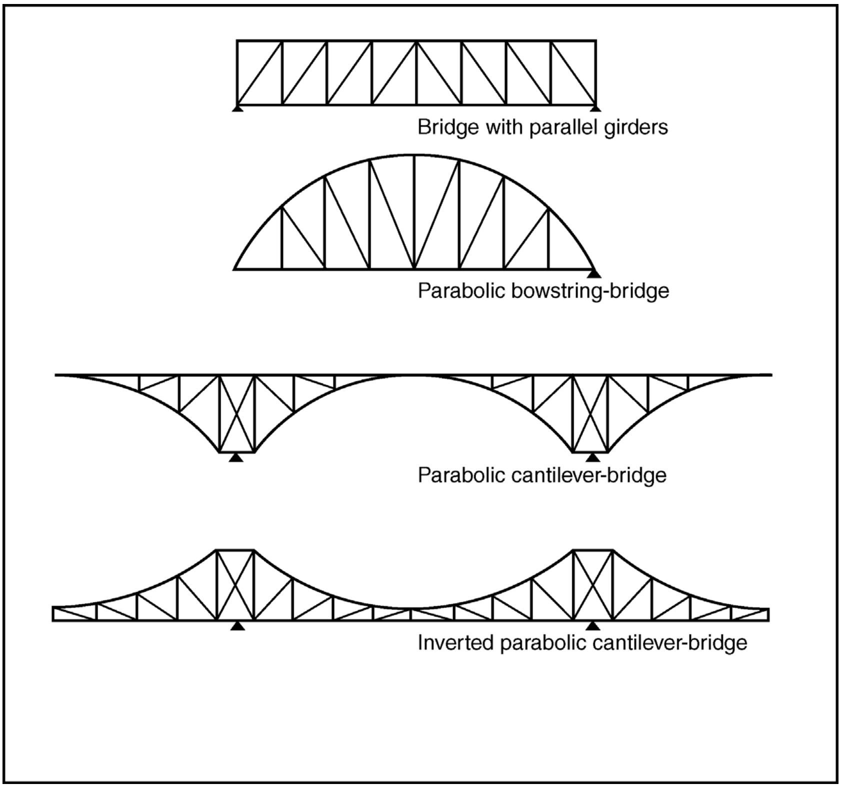

Figure 4.2 A diagram to show various forms of bridges that have been used as a model for the mammalian back. (a) Bridge with parallel girders; (b) parabolic bow-string bridge; (c) parabolic cantilever bridge; (d) inverted parabolic cantilever bridge. *Source:* Adapted from [2].

protagonists and is used in the discussions on how the equine back works. The model, however, contains an important conceptual error. The representation of the supraspinous ligament by the upper ledger and of the string of vertebral bodies by the lower ledger presumes tensional loading of the former and compressive loading of the latter, because ligamentous structures are not able to withstand compressive loads. In reality, the gravitational forces that act on bridges (and on the mammalian trunk) will cause compression in the upper ledger and tension on the lower one.

The Twenty-First Century – The 'Bow-and-String' Analogy

The current biomechanical concept of the equine back is that of the *bow and string*, in which the bow is the thoracolumbar vertebral column and the string is the 'underline' of the trunk, consisting of the linea alba, the rectus abdominis muscle and related structures. The model was first proposed by Barthez [6], but largely ignored until it was rediscovered by Slijper [2], based on his study of the positions of the spinous processes in a large number of species (Figure 4.3). It is the first concept that takes into account the entire trunk and not only the thoracolumbar vertebral column with adnexa, and presumes that there is a dynamic balance between the tension in the bow and string.

Factors that Influence the 'Bow and String'

There are many factors that influence the dynamic balance between tension in the bow and string and the ensuing intrinsic tension of the system (Figure 4.4).

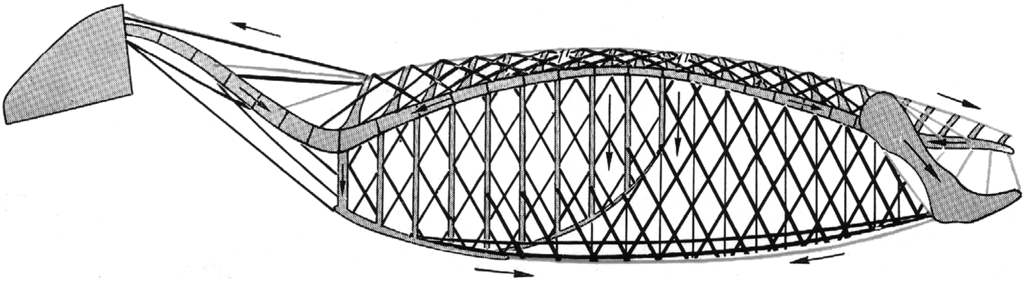

Figure 4.3 A diagram to demonstrate the 'bow-and-string' concept of the back according to Slijper [2]. The vertebral column is the bow and the ventral musculature and sternum are the string. The ribs, lateral abdominal musculature, spinous processes and ligamentous connections are additional elements. *Source:* Adapted from [7].

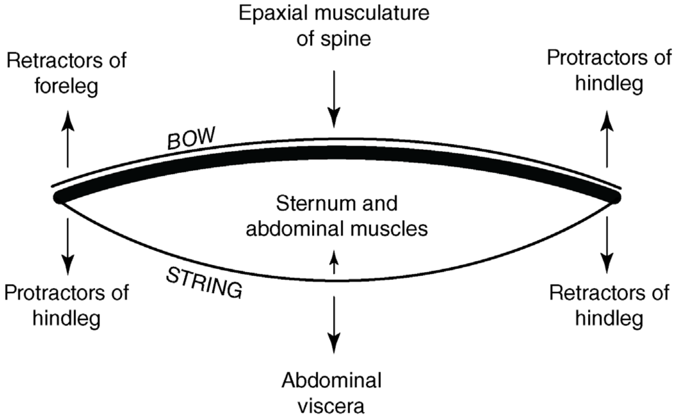

Figure 4.4 A diagram to show the factors that determine the motion of the back according to the 'bow-and-string' concept. Upward pointing arrows mean a flexing effect on the back; downward pointing arrows represent an extending effect.

- ***Gravitational forces*** will always act in a downward direction and hence tend to straighten the bow, i.e. extend the back or make it more hollow. Gravitational forces act on the back itself, but the gravitational pull on the large intestinal mass of the horse is a more important factor in extending the back. Pregnancy will aggravate this effect and old broodmares typically have a very hollow-backed conformation ('acquired lordosis', Chapter 14). Of course, every load on the back of the horse, including a rider, will have a similar effect.
- ***Active muscular action*** will also influence the dynamic equilibrium between the bow and string. Contraction of the ventral musculature will tense the bow, i.e. flex the back or make it more arched. In contrast to the belief of many lay people, contraction of the massive epaxial musculature will have the opposite effect, as the work line of these muscles runs dorsal to the axis through the centres of the vertebral bodies. The only dorsally located muscles that have a flexing effect on the back are the psoas muscles. However, these are located between the pelvis and the ventral aspect of the lumbar and last three thoracic vertebrae [7] and will principally affect lumbosacral flexion. There is no musculature ventral to the more

cranial thoracic vertebrae, which might flex this part of the spine.

- ***Limb movements.*** Pro- and retraction of the limbs will also affect the balance in the bow-and-string system. Protraction of the hind limbs will, through the forward position of the point of support and the anatomical connection between the gluteus medius muscle and the lumbar and sacral spinous processes through the gluteal and lumbodorsal fascia [7], flex the back or tense the bow. In a similar way, retraction of the forelimb will have the same effect. Protraction of the forelimbs and retraction of the hind limbs will have an opposite effect, i.e. produce a hollow (extended) back.
- ***The head and neck.*** A last, but not unimportant, factor that should be mentioned is the effect of the head and neck. Lowering the neck will tense the nuchal ligament and exert a forward rotating moment on the spinous processes of thoracic (T) vertebrae 2–6. These long spinous processes forming the basis of the withers provide a long lever arm, and traction on them in a forward direction will provoke tensing of the bow or flexion of the back. Elevation of the head will have an opposite effect.

Kinematics of the Equine Back

In order to begin to understand the kinematics of the equine back it is important to understand that the kinematics of any structure can be described as a product of 6 basic motions: three rotations and three translations.

For the equine spine the three *rotational* movements are the most important. Rotation around the dorsoventral or z-axis represents in most cases lateroflexion or lateral bending (LB), a rotation around the craniocaudal or y-axis represents axial rotation (AR) and a rotation around the axis perpendicular to the sagittal plane or x-axis represents ventrodorsal flexion–extension movements (FE) (Figure 4.5A and B). In some studies, x- and y-axes are interchanged, which is of course only a matter of definition and does not affect outcome.

In contrast to rotational movements, *translational* movements of vertebrae with respect to each other are very limited and therefore the translations along the 3 axes represent in fact the motion of the entire body, which will not be discussed in the context of this chapter. We can, therefore, concentrate solely on the rotational movements of the spine.

Research into equine spinal kinematics has long been mainly limited to work on postmortem specimens due to the large technical problems associated with work *in vivo.* However, even in the pre-World War II era some *in vivo* work was done. Krüger [4] used two cadaver horses to examine the kinetics of the thoracolumbar column and its movements. This was achieved by manipulating long metal rods that had been inserted in holes drilled in a number of vertebrae, while the pelvis remained fixed. He determined maximal motion in dorsoventral and lateral directions, and compared the outcome with results from *in vivo* work in 3 horses. The horses were filmed from the side (lateral view) and from above (the camera had been fixed in the branches of a tree!), after marking the midline and two lines perpendicular to it, at the withers and at the pelvis, with white paint. From these experiments Krüger [4] noticed that motion *in vivo* was considerably less than the maximal ranges of motion found in the cadaver specimens. This observation was confirmed some 40 years later when Jeffcott and Dalin [8] concluded that, in comparison to other species, the natural flexibility of the horse's backbone was very limited.

A number of further studies on back flexibility have taken place. In a large study conducted at the Western College of Veterinary Medicine in Saskatoon, Townsend and co-workers [9] dissected 18 equine spines and marked them with Steinmann pins placed in the geometric centre of the ventral surface of each vertebral body, perpendicular to a plane through the long axis of the thoracolumbar spine and the transverse processes.

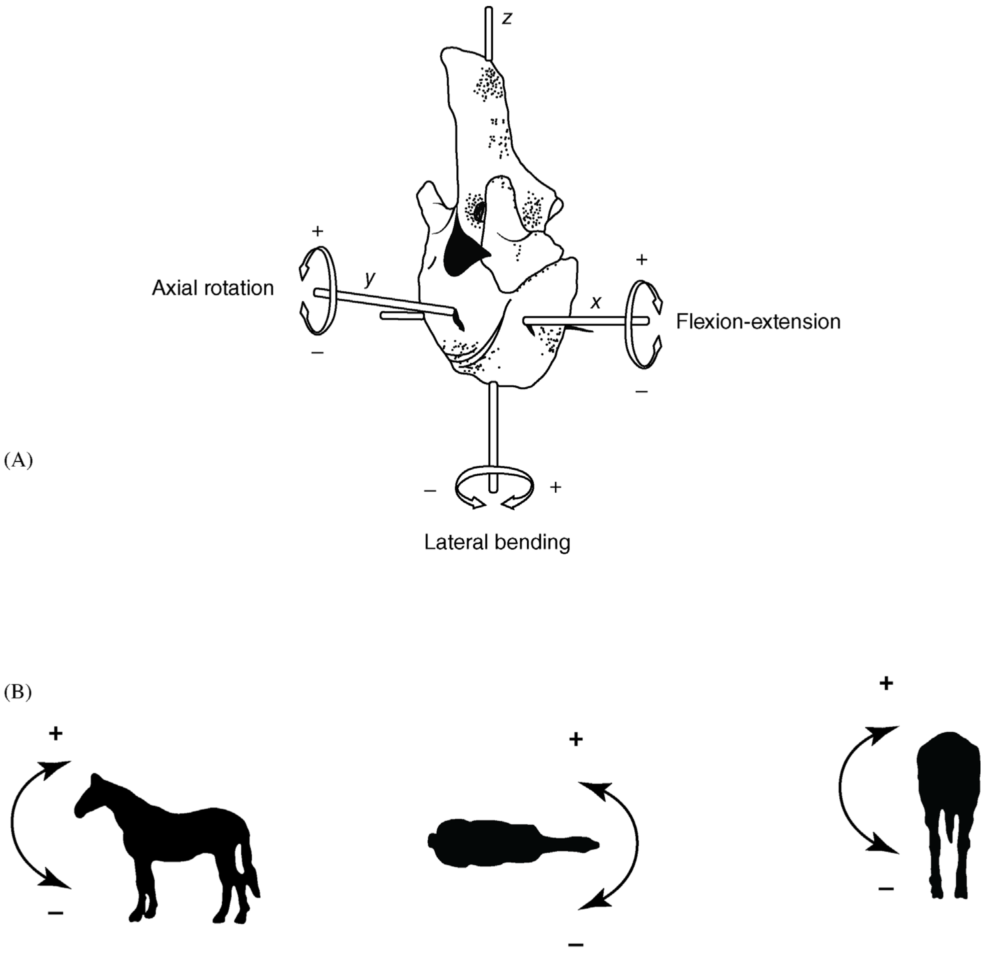

Figure 4.5 (A) A diagram to show the basic movements of the back depicted as rotations of an individual vertebra around the three axes of an orthogonal coordinate system. (B) A diagram to show the three basic movements of the equine back: flexion–extension (FE) (A), lateroflexion or lateral bending (LB) (B) and axial rotation (AR) (C).

The sacrum of each spine was fixed in a clamp and manual pressure was used to provoke FE, LB and AR, which were recorded photographically. Conditions prior to and after removal of the rib cage were compared.

In this study, dorsoventral movement (FE) was found to be maximal in the lumbosacral joint (which may be either the transition between L6 and S1 or between L5 and L6). This study demonstrated that the range of motion (ROM) at this site could attain approximately 25°, which was considerably more than in other parts of the spine where FE ROM did not exceed 4° in the area between T2 and L5/L6, and was 6–8° at the junction of T1 and T2. Lateral bending was largest at T11/T12 with 10–11° and decreased in both the cranial and caudal direction to about 4° in the cranial thoracic area and not more than 1° at the last lumbar vertebrae. Axial rotation was most prominent in the region T9–T14 (up to 5°) and decreased in the cranial (2–3°) and more so in the caudal direction (1°), with the notable exception of the lumbosacral joint (2–3°). Removal of the ribs did not affect FE or LB, but significantly increased AR in the cranial thoracic region. The regional differences in the mobility of the segments of the thoracolumbar spine could be related to anatomical peculiarities of the intervertebral joints and other anatomical or acquired structures such as the frequent fusion of the transverse processes of the last lumbar vertebrae, explaining the extreme rigidity of this part of the equine spine [10].

Denoix [11] performed a comparable, but more comprehensive, *in vitro* study on cadaver specimens. He included the influence of the position of the head and neck and paid more attention to the effect of the position of a given region of the thoracolumbar spine on the mobility of another region. In this study, FE was found to be larger in the caudal thoracic part (T14–T18) than in the rest of the spine, with the obvious exception of the lumbosacral joint. Cervical flexion provoked flexion in the thoracic spine, but also a decrease in FE range of motion in the lumbar area, which was compensated for by an increased mobility at the lumbosacral joint. In the same study, the instantaneous centres of rotation of the intervertebral joints were determined, which appeared to be situated within or near the next adjacent vertebral body. In a study focusing more on the lumbosacral and iliosacral regions, the same author applied forces on isolated pelvises in transverse, axial and dorsoventral directions to assess possible deformations of the structure generated by the forces of locomotion. In the study on the iliosacral region it was shown that the pelvis resisted high loads in the longitudinal direction (i.e. in the direction of impulse in the moving horse), but is more susceptible to forces in the other two directions, which may be substantial under conditions like taking turns at high speed on insufficiently banked tracks, rearing, etc., and might provoke damage to the pelvic and sacroiliac ligaments. The lumbosacral region was, as in preceding studies, very rigid with respect to FE, with both AR and LB being very limited as well, the latter movement being virtually impossible in the caudal lumbar area (caudal to L4) because of the formation of joints between the transverse processes. It was hypothesised that this high degree of rigidity could lie at the base of the region's tendency to develop intervertebral ankylosis [12].

The relatively frequent diagnosis, or at least suspicion of sacroiliac pathology as a cause of poor performance or of subtle and obscure hind limb lameness (Chapter 15), has boosted the interest in the kinematics of this very inaccessible area. In an elaborate study using a number of dissected pelvises with pins placed at strategic sites and a state-of-the-art kinematic analysis system, Degueurce et al. [13] showed that the amount of nutation and counternutation (rotation of the sacrum respective to the pelvic bones in the sagittal plane) did not pass 1°, which is too small to be detected in the living horse. Goff et al. [14] confirmed this observation, but showed a larger range of motion in the transverse plane, when lateral and oblique forces were applied to the pelvis, which may give more insight into the physiological role of iliosacral mobility and might explain the relatively large importance attributed to the area in clinics (Chapter 15).

Kinematics of the Equine Back – *in vivo* Research

Whereas studies on the kinematic analysis of limb movement appeared in large numbers from the early 1970s onwards [15], *in vivo* work on back kinematics remained virtually absent for almost another 3 decades. This was primarily due to the technical difficulties involved in measuring the small movements of the equine thoracolumbar spine.

Skin Marker Based Measurement Techniques

The first attempts at measuring equine back kinematics *in vivo* all focused on FE, which is easiest to measure and is influenced least by skin displacement when using skin markers. Audigié et al. [16] used a method developed by Pourcelot et al. [17] and placed 5 skin markers in the midline over the top of the withers, the 12th and 18th thoracic vertebrae, the tuber sacrale and the sacrocaudal junction. The markers were used to measure what was called the thoracic angle, the thoracolumbar angle and the lumbosacral angle in sound trotting horses. The range of motion for all three angles was shown to be less than 4° and variability, both intraindividual and interindividual, was low. Horses extended the back during the first part of each diagonal stance phase and flexed in the last half of the stance phase. Comparing the kinematic data with electromyographic data obtained earlier [18] showed that activity of the epaxial musculature tended to limit FE motion, rather than cause it. A similar conclusion was reached by Licka et al. [19], who presumed, based on an electromyelogram (EMG) study, that the main action of the *longissimus dorsi* muscle was the stabilisation of the vertebral column against dynamic forces. Licka and Peham [20] used a kinematic analysis system and skin markers on T5, T10, T16, L3 and on the sacrum in an attempt to objectify the induction of maximal flexion using manual diagnostic tests. Flexion–extension and LB were investigated and expressed as mean transversal movement (LB) and mean vertical flexion (FE) relative to the height of the withers. Although perhaps not illogical, this measure makes comparison with most of the other literature, where back motion is expressed in degrees, difficult. In a follow-up study, in which LB and FE were induced in the standing horse under simultaneous registration of the positions of markers on the spinous processes of T5, T12, T16, L3 and S3 and EMG activity of the *Longissimus dorsi* using surface electrodes, it was concluded that T12 was the best place to take EMG recordings. The EMG on both sides of the spinous process of T12 had the highest and the EMG at the height of L3 the lowest amplitudes [21].

The same research group investigated back kinematics in walking horses on a treadmill. They found maximal LB at L3, which is further caudal than in most other studies. Flexion–extension was maximal at the sacrum. This motion reflects in fact the upward–downward motion of the pelvis as induced by the hindlimbs; it cannot be compared to the results of the *in vitro* studies as in those studies the pelvis was fixed and thoracolumbar motion was assessed relative to this fixed point.

Kinematic analysis methods using skin markers always suffer to a certain extent from the so-called *skin displacement artefact*, which is caused by the fact that the skin will not always exactly follow the motion of the underlying bone, a phenomenon that was actually noted 100 years ago [22]. Skin displacement will be of relatively minor importance for FE where the marker will directly follow the movement of the underlying spinous process, but the coupling of LB and AR during any movement of the spine out of the sagittal plane [23] indicates that the composed movements of markers under that circumstance cannot be unambiguously broken down into the lateral bending and axial rotation components. Therefore, equine spinal kinematics could never be described fully using skin marker based techniques.

Invasive Marker Measurement Techniques

The only way to overcome the problems associated with measurements using skin markers was to resort to invasive techniques in which a rigid connection is made between the vertebra and an external marker or measuring device. Haussler et al. [24] used such an approach. They implanted Steinmann pins into a number of spinous processes and connected the pins by liquid metal strain gauges, positioned according to the three axes of rotation. The technique is accurate (resolution of 0.07° in FE and about 0.5° in AR and LB), but laborious and simultaneous measuring of the motion of a substantial number of vertebrae is difficult. In their first paper Haussler et al. [24] reported a ROM of FE at the lumbosacral junction at walk of 4°. AR and LB were on the order of 1° at that site. In a follow-up paper the same technique was used to investigate segmental motion at T14–T16, L1–L3 and L6–S2 at walk, trot and canter. The largest ROM for all three rotations was found at the lumboscral junction with the largest ROM for the canter and the smallest

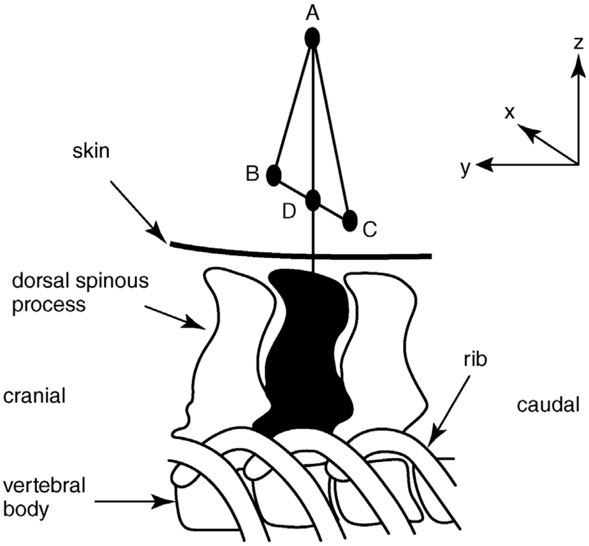

Figure 4.6 A diagram to show a marker device with four markers (A–D) attached via a Steinmann pin to the spinous process of a vertebra and oriented in the laboratory coordinate system (*x*, *y*, *z*). (From Faber et al. [26] with permission from the American Veterinary Medical Association.)

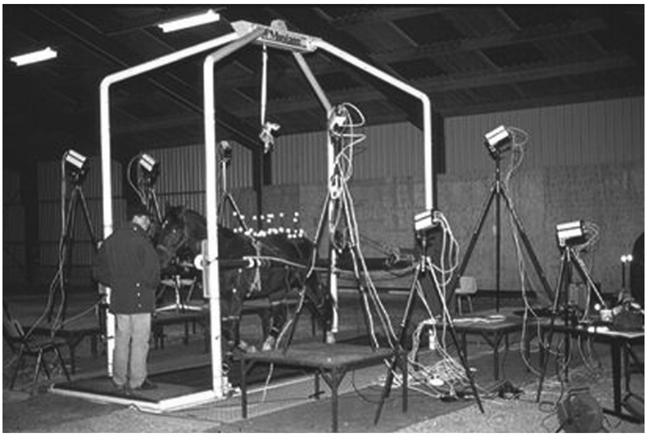

Figure 4.7 A photograph to show a horse on the treadmill with marker devices attached to Steinmann pins implanted into the spinous processes of T6, T10, T13, T17, L1, L3, L5 and S3, and both tubera coxae.

for the trot. ROM for FE, LB and AR at canter were approximately 5, 3.5 and 4.5° [25].

The approach chosen by Faber et al. [26] used a technique that also was based on the implantation of Steinmann pins into the spinous processes. Pins were placed under fluoroscopic guidance in the spinous processes of T6, T10, T13, T17, L1, L3, L5, S3 and in the tips of the coxal tubers. To this pins custom-made devices were attached carrying reflective markers that could be detected by the ProReflex®[1] kinematic analysis system (Figure 4.6). In this way, a rigid connection was realised between the optical markers and the vertebral body and the 3-D motion of the markers therefore represented the movements of the underlying vertebrae. For data analysis, a newly developed method was used that allowed for the determination of 3-D spinal kinematics without defining a local vertebral coordinate system [27]. Measurements were performed on a treadmill at walk, trot and canter (Figure 4.7), and kinematic motion patterns of the vertebrae studied were established [26,28,29]. Motion patterns of all 3 basic rotations had a sinusoidal shape related to the stride cycle. Flexion–extension is induced

---

[1] Qualisys Medical AB, Gotheburg, Sweden.

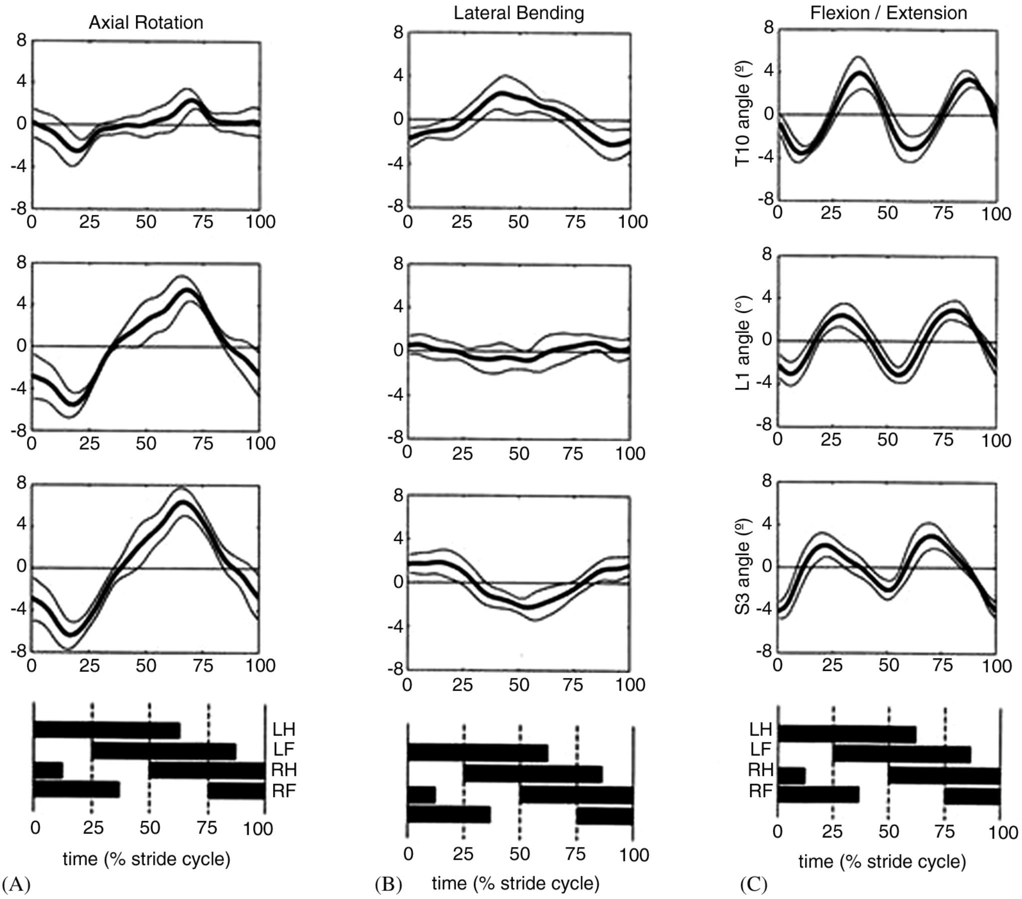

Figure 4.8 A diagram to show the mean (thick line) and standard deviation (thin lines) of the motion patterns of three vertebrae (T10, L1 and S3) of five horses walking on a treadmill at a speed of 1.6 m/s. The stride cycle is represented by the bars below (LH: left hind; RH: right hind; LF: left fore; RF: right fore). The bar is closed when the limb is in contact with the ground (stance phase). (A) Axial rotation; (B) lateral bending; (C) flexion–extension. (From Faber et al. [26] with permission from the American Veterinary Medical Association.)

by pro- and retraction of each hind limb and therefore shows two peaks for each entire stride cycle whereas LB and AR have a left and a right component, which is reflected by the positive and negative parts of a single sinus that is generated during a stride cycle (Figure 4.8). Flexion–extension motion at walk was approximately 4° at T6 and remained fairly constant at 8° for all more caudally located vertebrae. Lateral bending was maximal for the area round T10 and for the pelvic region (approximately 5°), and less in the more central region of the spine (approximately 3°). Axial rotation increased gradually from 4° at T6 to 13° for the tuber coxae. Spinal motion is considerably less at trot than at walk. Flexion–extension ranged from 2.8 to 4.9°, LB from 1.9 to 3.6° and AR from 3.1 to 5.8° at trot [28]. At canter, maximal ranges of motion for FE, LB and AR were 15.8 ± 1.3°, 5.2 ± 0.7° and 7.8 ± 1.2° respectively [30]. The largest relative FE motion was, not surprisingly, found between L5 and S3 with 8.6°, which is, however, considerably less than the maximal values found during the *in vitro* experiments alluded to earlier, but a little more than reported by Haussler et al. [25]. Variability of spinal motion appeared to be gait-dependent and to vary per type of

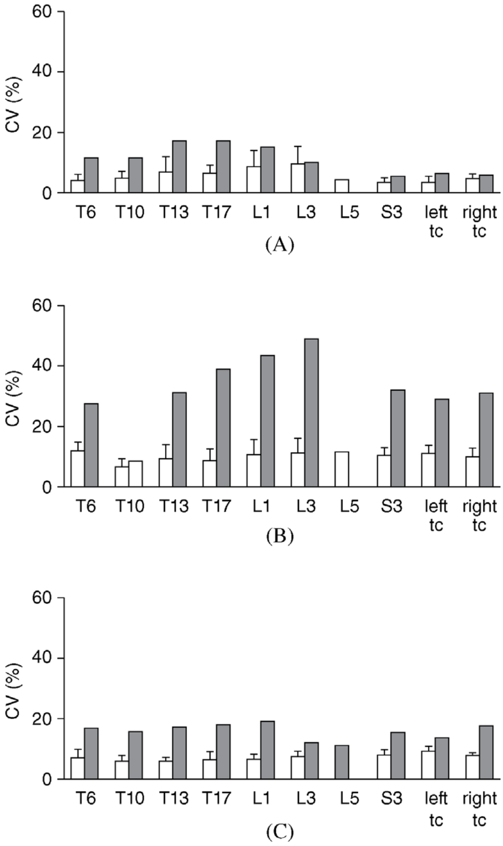

Figure 4.9 A diagram to show the within-horse (open bars) and between-horse (bars) variability at canter in (A) flexion–extension, (B) lateral bending and (C) axial rotation, expressed as a coefficient of variability (CV, as percentage of the range of motion, or ROM). *Source:* Adapted from [31].

motion (FE, LB, AR). At walk, within horse variability (WHV) was lowest at approximately 6% for AR, slightly more for FE (6–8%, but for T6 13.2%) and most for LB (7.8–18.2%). Between horse variability (BHV) was 2–3 times higher than WHV for most rotations and vertebrae, and was again higher for LB (Faber et al. [26]). At trot, LB was the most constant motion (WHV 5.7–8.2%), for FE and AR values it ranged from 5.9 to 12.9%, and with BHV 4–5 times higher than WHV [28]. At canter, WHV was lowest for FE (3.1–9.0%), followed by AR (6.3–11.6%) and LB (8.4–12.5%). Here again, BHV values were much higher (Figure 4.9) [30].

Further Modification of the Skin Marker Measurement Technique

Based on the invasively acquired data, Faber et al. [29] developed and validated a skin marker based method of assessing kinematics that could be used in clinical practice, which is obviously not possible for invasive methods. The method allows for the calculation of ranges of motion of specific vertebrae, which gives an indication of overall spinal mobility, but also for the calculation for so-called angular movement patterns (AMP's). The AMP describes the position of a given vertebra in space with respect to two other vertebrae, one on either side. For example, to calculate the flexion–extension AMP of T10, the 3-D coordinates of T6 and T13 are projected on to the y–z plane and a line (line 1) is drawn between these points. Assuming that the vertebral column is curved according to the bow-and-string concept [2] and that T10 is located midway between T6 and T13, a second line (line 2) is drawn through the projection of T10 and parallel to the first line. The degree of FE for T10 can then be calculated from the orientation of line 2, relative to the horizontal axis. For LB, a similar approach is possible with projection on the x–y plane. AR can only be calculated for the sacrum and is determined from the position of the projection of the tuber coxae markers on the x–z plane, assuming negligible motion in the iliosacral connection [29]. Another parameter that can be used to assess thoracolumbar kinematics is the intravertebral pattern symmetry. For walk and trot, which are symmetrical gaits, the pattern of the AMP during the first half of the stride should be identical to the second half. The amount of similarity, calculated as the correlation coefficient between the patterns during these first and second halves, is called the intravertebral pattern symmetry. The non-invasive skin marker based analysis method was tested for repeatability with respect to day-to-day variation by measuring the same horses on 5 consecutive days, and in 2 lab settings with different breeds of horses (Warmbloods and Standardbreds). There was a high degree of between-stride and between-day repeatability in the spatiotemporal variables and in the time-angle diagrams of the vertebrae studied. Variability between horses was considerably larger for all parameters. Between the two labs and breeds small differences were found in range of motion values. It was concluded that this method for the non-invasive analysis of equine back kinematics provided reliable and repeatable data and hence could be used in a more clinical setting [31]. This validated method has further been optimised and available as a user friendly customised programme (BacKin®[1]), which has been used successfully in several applications of equine back kinematics for the study of clinical and equestrian questions.

Applied Kinematics of the Equine Back

A number of different parameters have been studied using the marker-based analysis system that was developed after the invasive experiments described above. These include physiological factors that may influence back motion, the effects of therapeutic or diagnostic interventions on back movement, the effect of a saddle, the effect of various head and neck positions on back mobility, the influence of induced fore and hind limb lameness, the influence of naturally and induced occurring back pain, and the effects of chiropractic treatment.

Physiological Factors

Johnston et al. [32,33] focused on physiological factors. In a study on the effect of conformation on back movement they noticed that horses with longer strides have more FE ROM in the caudal saddle region, which was evident only at walk. A long thoracic back resulted in more LB in the lumbar area and there was a negative relationship between the curvature of the midthoracic back and LB at L1/L3 and axial rotation of the pelvis [32]. In another study that attempted to create a database for normal kinematics of the equine back as a reference source, they measured 33 normally functioning riding horses and evaluated the effect of physiological variables. Significant differences were found with respect to use and gender with larger LB at T10 and T13 for dressage horses compared to show jumpers. Range of motion for LB was greater at T10 in mares compared to geldings, but less at L5. There was a decrease of FE ROM with increasing age [33].

Therapeutic or Diagnostic Interventions

Manual Manipulation and Rehabilitation

Faber et al. [34] used the newly developed technique to assess the effect of manual manipulation on back motion and symmetry of movement. Manual treatment of alleged back problems, according to either chiropractic, osteopathic or other principles, has become very popular in recent years, but is not uncontested. Many professionals still take a very sceptical stance and doubt whether the equine thoracolumbar spine can be manipulated at all by human muscular power. Whether or not manipulation may have some effect, it is certain that the popular belief of “realigning a vertebra” after an alleged “subluxation” is not compatible with the anatomical reality and should be discarded as a possible mechanism [35]. In this case report it was demonstrated that manual treatment indeed could affect vertebral motion patterns and their symmetry and that the effect lasted (partly) for at least 7 months [34]. The *caveat* that comes from this study is that the positive clinical effect did not seem to be directly related to the improved symmetry of movement, but was brought about by a change in trainer.

More studies on the effect of chiropractic manipulations on equine spinal kinematics using much larger numbers of horses have been performed and have confirmed that chiropractic interventions can alter back kinematics. Haussler et al. [36] showed that spinal manipulative therapy had a beneficial effect on thoracolumbar kinematics in horses in which back pain had been induced by the implantation of fixation pins. Sullivan et al. [37] used chiropractic techniques in various groups of asymptomatic horses and could show that manipulation had a more profound effect on back kinematics than massage or treatment with phenylbutazone [38]. Gómez Álvarez et al. [39] used chiropractic treatment in horses with signs of back pain and showed that the main overall effect of manipulation was a less extended thoracic back, a reduced inclination of the pelvis and improvement of the symmetry of the pelvic motion pattern. However, in this study changes in back kinematics were subtle and not all of them were still measurable at a second measurement session 3 weeks after treatment. Spinal kinematics have also been used as an outcome parameter for a study on the effect of a water treadmill exercise. In that study it was shown that there was a significant increase in axial rotation when the water was at the level of the carpus or higher and that lateral bending was significantly reduced with water levels higher than the elbow. Pelvic flexion was increased with regard to baseline at all water levels higher than the hoof [40]. Lastly, spinal kinematics have been used to assess the effects of mobilization exercises of the head and cervical region, aiming at reducing neck pain and improving rehabilitation, following regular practice in the human field [41,42].

Effect of Clinical Pathology

The diagnosis of back pain is a controversial item in itself. Haussler and Erb have introduced the algometer, a device that basically measures the pain threshold when applying pressure to certain areas of the back, as an interesting device that may help in quantifying back pain [43,44]. However, in many studies back pain is diagnosed by (repeated) palpation, which is a largely subjective procedure. Wennerstrand et al. [45] compared sound horses with horses with back pain and found a reduction in FE and AR ROM in the symptomatic horses, with a concomitant significant decrease in stride length, which is in accordance with earlier reports [34,46]. Lateral bending was increased at T13, possibly as a kind of compensatory motion. Most of these horses suffered from kissing spines or muscle soreness. Diagnoses were made by palpation, radiography and scintigraphy, but no local blocking, was performed. The same group assessed the effect of the application of local anaesthetic blocks in the interspinous spaces (T6–L2) of asymptomatic, clinically sound horses. Local blocks resulted at walk in an increase of ROM of FE in virtually all segments of the back and of LB at T10, L3 and L5. Also lateral excursion (defined as the lateral displacement of the markers T10, T13, T17, L1, L3 and L5 in relation to the line connecting T6 and S3) increased for all segments. At trot, the effect was much less. Also the injection of sodium chloride resulted in increased mobility, though to a lesser degree. The mechanism was thought to act via an influence on propioception of the multifidus muscle [47]. This muscle is known to play a very important role in the stabilisation of the back in humans and dysfunction of the muscle is a frequent cause of back pain [48]. Recent research suggests a similar role for this muscle in the horse [49].

The influence of lameness on back kinematics and *vice versa* has been a controversial item for a long time. In a field study Landman et al. [50] found indications of both lameness and back pain in 26% of the animals belonging to a relatively large ($N = 805$) population of patients presented for orthopaedic problems. In a presumably asymptomatic control population that consisted of horses presented for prepurchase exams ($N = 399$), concurrence of back problems and lameness was found in 5% only. Dyson [51] diagnosed concurrent forelimb and hindlimb lameness in 46% of horses with thoracolumbar or sacroiliacal pain. Though interesting, the figures give, however, no evidence about a possible causal relationship. In an attempt to learn more about cause and effect, Jeffcott et al. [52]

induced transient back pain in trotters by injecting lactic acid into the epaxial musculature. They did not see an effect on linear and temporal stride parameters (stride length, stride frequency, pro- and retraction angles); a stiffer back was noted, but thoracolumbar kinematics were not quantified.

In a similar study, the same procedure was used in Dutch Warmbloods. There were also no effects on the spatial and temporal gait characteristics, but back kinematics were clearly affected, showing a two-stage response that was attributed to an acute reaction to the painful injection and ensuing muscle stiffness in the following days [53]. From the other side, it has been shown that fore- or hindlimb lameness may alter biomechanics of the back [17,54]. Horses showed a moderate but evident lameness in these studies. The effect of very subtle forelimb lameness on back kinematics have also been studied. It appeared that a very light lameness (maximally 2/5 [55]) increased the vertebral range of motion and changed the pattern of thoracolumbar back movement in the sagittal and horizontal planes, presumably in an attempt to move the centre of gravity away from the lame side and reduce the force in the affected limb [56]. A comparable study in which a subtle lameness was induced in the hindlimbs reported hyperextension and increased ROM of the thoracolumbar back, a decreased ROM of the lumbosacral segment and rotational motion changes of the pelvis [57]. It was concluded that already a slight lameness affects back motion and might hence play a role in the pathogenesis of back problems. It should be stated that these studies have investigated the acute effect of lameness on back motion, whereas in the clinical setting chronic lameness can be presumed to have more influence. Chronic lameness is, however, much more difficult to mimic in an experimental situation.

Performance

In an in-depth longitudinal study on the effects of early training on jumping ability and on the early detection of jumping potential, Santamaría [58] used many kinematic parameters, among which kinematics of the back. It was shown that jumping technique, including the use of the back, to a large extent persisted from foal to adult age [59]. At the end of the 5-year study period, performance was judged by way of a puissance competition. Although back motion in itself was not discriminative between good and bad jumpers, the degree of hind limb retroflexion (*i.e.* backwards extending of the hind limbs relative to the back when clearing the jump) was one of the kinematic parameters that were different between the good and the bad jumpers [60].

Saddlery

De Cocq et al. [61] investigated the effect of a saddle with and without added extra weight on back kinematics. They compared 4 conditions: no tack, a girth, a saddle, and a saddle with 75 kg of lead attached to it in horses walking, trotting and cantering on a treadmill. The weighted saddle appeared to have, at all 3 gaits, an overall extending effect on the back, but ROM remained the same (Figure 4.10). At canter, the same was true for the saddle-only condition. There was a change in limb kinematics too, with forelimb retraction increasing. This observation is nice indirect evidence for the bow-and-string concept: the added weight on the back tends to extend the bow and the horse tries to counteract this influence by more retraction of the forelimbs, which has a flexing effect.

Rhodin et al. [62] and Gómez Álvarez et al. [63] studied the influence of the position of head and neck on back kinematics. The item is of interest from an equestrian viewpoint. The rules of the *Fédération Equestre Internationale* (FEI) describe the desired position of head and neck for most dressage activities as follows: 'The neck should be raised, the poll high and the head slightly in front of the vertical.' This is a position that is considerably more upright than the position the horse will assume by nature. Most classic training systems, which date back hundreds of

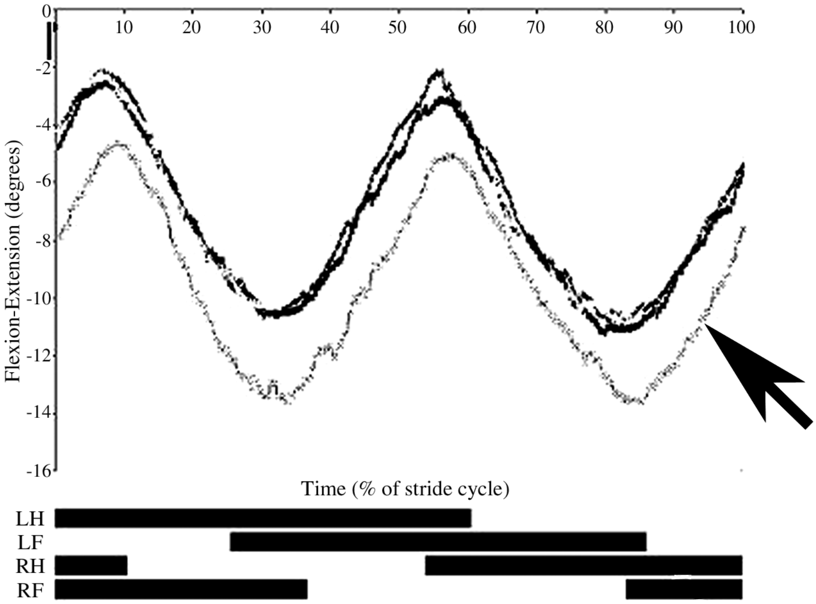

Figure 4.10 A diagram to show the range of motion (ROM) during a single stride cycle of T13 in four conditions: without a saddle, with only a tightened girth, with saddle and tightened girth, and with loaded saddle (75 kg) and tightened girth. Only the last condition (arrow) differed significantly and resulted in an overall increase in extension. However, ROM (maximal flexion minus maximal extension) remained the same. LH: left hind; RH: right hind; LF: left fore; RF: right fore. (Adapted from De Cocq et al. [61] with permission from Equine Veterinary Journal Ltd.)

years [64], use this position, or positions close to it, also during training. However, in the early 1970s it became *en vogue* in show jumping to train horses with a hyperflexed neck and a much lower and deeper position of the head, which is to a certain extent rolled up against the chest. This position was later baptised 'Rollkur' in the German literature [65]. The technique was taken over by a number of dressage riders, some of who became extremely successful, but the technique became heavily disputed because of an alleged impact on animal welfare. This has led to much debate in the lay press [66–68]. In an attempt to objectify the effect of head and neck position Rhodin et al. [69] compared the free or natural position with a higher and a lower position, effectuated by side reins, in unridden horses on a treadmill. They showed a significant reduction of FE and LB ROM of the lumbar back with the head in a high position. Also, AR was reduced. The low position, in which the head and neck were not as hyperflexed as in the 'Rollkur' position, did not differ significantly from the free position, but showed a tendency towards a restriction of movement as well. Gómez Álvarez et al. [63] studied the item more extensively as part of a large international collaborative project in which horses of Grand Prix level were measured while walking and trotting, ridden and unridden, on a treadmill with an inbuilt force plate under simultaneous motion capture by a 12-camera ProReflex®[1] system. Six head and neck positions were studied (Figure 4.11), of which head and neck position (HNP) 2 resembled the position as defined by the FEI rules, and HNP4 came as close as possible to the 'Rollkur' position. It showed that differences in head and neck positions predominantly affected the vertebral angular motion patterns in the sagittal plane (i.e. FE). The positions in which the neck was extended (HNP2, 3, 5) increased extension in the anterior thoracic region, but reduced flexion in the posterior thoracic and lumbar regions. For

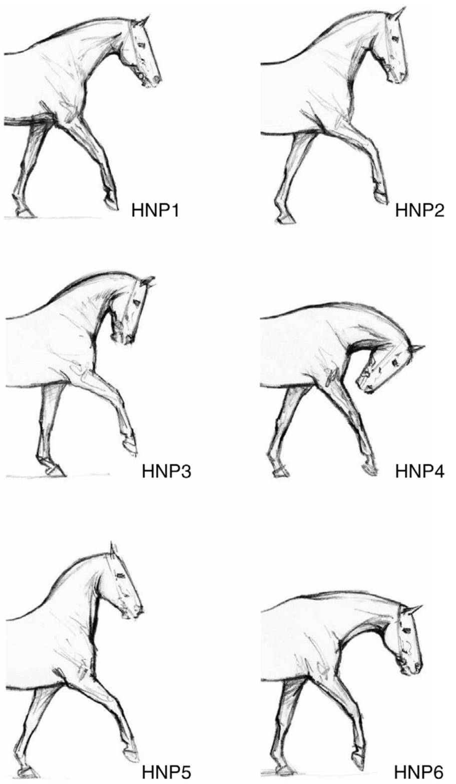

Figure 4.11 A diagram to show head and neck positions (HNPs). HNP1: control (head and neck unrestrained); HNP2: neck raised, bridge of the nose in front of the vertical; HNP3: as HNP2 with bridge of the nose behind the vertical; HNP4: head and neck lowered, nose behind the vertical; HNP5: head and neck in extreme high position; HNP6: head and neck forward downward. (From Gómez Álvarez et al. [63] with permission from Equine Veterinary Journal Ltd.)

HNP4 the pattern was opposite. Flexion–extension ROM was reduced at walk in the lumbar region in HNP2 and 5, and at trot also in HNP3. In HNP5 (extremely high head) the effect was largest and this was the only position in which intravertebral pattern symmetry was negatively affected and hindlimb protraction was reduced. In the low and deep position (HNP4) there was an overall increase in FE ROM, in both the thoracic and the lumbar area (Figure 4.12). It was concluded that a very high position of the head seems to greatly disturb normal kinematics, but that the increased mobility of the back at HNP4 lends some credibility to the statement of a number of trainers that a low position of head and neck may be a useful aid in the gymnastic training of a horse [61]. The analysis system for thoracolumbar kinematics developed by Pourcelot et al. [17] and first applied by Audigié et al. [16] was used to try to discriminate between good and bad jumpers on the basis of back kinematics. Several differences between the groups were found, among which an increased flexion of the thoracolumbar and lumbosacral junction before take-off in the bad jumpers, which might indicate a less efficient strutting action when forward movement is converted into upward movement [70]. During the airborne phase, lumboscral extension was less in the bad jumpers.

Robert et al. [71] used the same technology to analyse the effect of treadmill speed on back kinematics (and muscle activity using surface electromyography). Horses were trotted at speeds from 3.5 to 6 m/s. It was shown that the amplitude (ROM) of FE and the maximal flexion angles decreased with increasing speed, whereas the extension angles remained the same. Muscle activity increased also, confirming the view that the large trunk muscles (*M. longissimus dorsi* and *M. rectus abdominis*) act to restrict back movement, rather than actively enhancing or inducing it.

An entirely different approach was chosen by Keegan *et al.* [72]. They used skin markers in 12 normal and 12 atactic horses and analysed the data by computer-assisted fuzzy clustering techniques that were based on the calculation of signal uncertainty. It appeared that the movement of the lumbar marker (both with respect to LB and FE) was among the few markers that were able to discriminate between normal horses and horses suffering from ataxia.

Conclusions and Possible Future Developments

Much has happened in the field of back kinematics since Jeffcott spoke the following

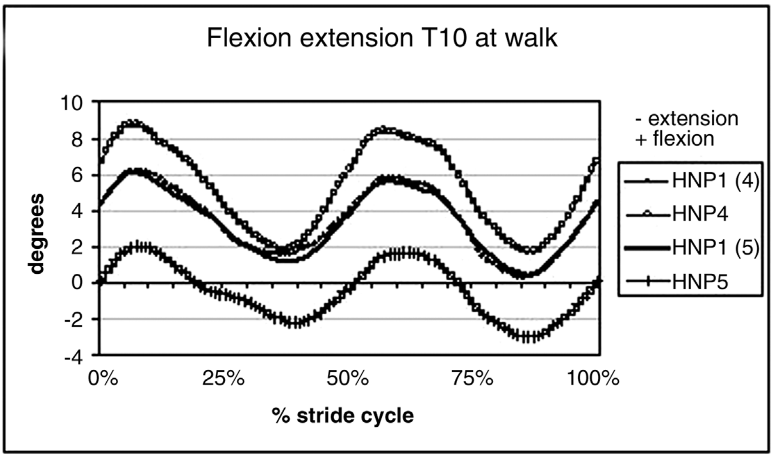

Figure 4.12 A diagram to show flexion–extension angular motion pattern (AMP) of one horse (T10 at walk). The curves represent head and neck positions 4 (HNP4) and 5 (HNP5). HNPs were compared with speed-matched trials with the head and neck in the natural position, indicated as HNP1 (4) and HNP1 (5). The stride cycle starts with the left front limb. (From Gómez Álvarez et al. [63] with permission from Equine Veterinary Journal Ltd.)

words during the 4th Sir Frederick Hobday Memorial Lecture in 1979: 'The biomechanics of the equine thoracolumbaspine have been considered to some extent, but it requires much greater study if the pathogenesis of the various thoracolumbar disorders are to be properly understood' [35]. We have since learnt much about the maximal ranges of motion of various segments of the equine thoracolumbar spine and the anatomical constraints that limit these motions through both *ex vivo* and *in vivo* research. The clinical evaluation of the motion pattern of the equine back is as difficult as it was in the 1970s, but kinematic analysis techniques have improved vastly and we are now able to document the kinematics of the equine back in a reliable and repeatable way in terms of ranges of motion and angular motion patterns of individual vertebrae, even if these values are not greater than a few cm or a couple of degrees. We should, however, recognize that the general drawbacks of kinematical analysis when used for diagnostic purposes still apply. Aberrant kinematic patterns are in most cases not very specific indicators of back pathology because there are many more possible pathological conditions than ways horses can alter their locomotion pattern. Further, there is a large grey area between normal and pathologic locomotion patterns. Because in patients almost invariably no kinematic data are available that were captured prior to the onset of the problem and individual variation in gait patterns is large, it is often impossible to draw conclusions based on a single measurement [73]. It has become clear that the item of individual variation is important, particularly in the case of thoracolumbar kinematics, especially at the walk and the canter and with respect to LB [26,30].

The measurement of back kinematics now has become a standard element of various analysis protocols for equine kinematics and back kinematics have been used very successfully to assess the effect of a number of conditions and interventions on equine motion. Because the back bridges the gap between the four extremities and back kinematics reflect, through the bow-and-string principle, what happens to the trunk, back kinematics are an excellent parameter to study the influence of any intervention on the animal as a whole. There is a need for hard, scientific data in this area, as has been demonstrated by the discussion on the use of the 'rollkur', 'overbended' or 'hyperflexed' position of the head in dressage training, which was based on emotion and prejudice rather than on scientifically proven facts. It should be realised, however, that in items where the ethical acceptability of certain practices is questioned, a more comprehensive approach is required and biomechanical data will have to be complemented by facts from entirely different disciplines.

Telling the future is a hazardous undertaking, but it takes little imagination to predict that, as in any branch of kinematics, modelling will become more important in the study of equine thoracolumbar kinematics. Preliminary studies have already been published by the group from Vienna, who presented a segmental model of the back and simulated a regional increase in stiffness to study the effect on back motion as a whole [74,75] and compared the outcome to data generated by *ex vivo* measurements on dissected spines [76]. As with any model, there is a risk that these models are going to lead a life on their own and the validation with *in vivo* acquired data remains essential. Generating good quality input data on equine back movement for these models is not very easy, and neither is the refining of the model to approach real-life conditions, given the complex structure of the back. However, more and more input data on back kinematics, force distribution under the saddle and muscle activity are becoming available, making input from more than only kinematic data in the model possible [77]. Also, developments in the modelling and animation area, partly driven by the entertainment industry, happen fast. There is little doubt that much progress will be made in the next few years. Progress in modelling of back function has not been as fast as expected over the last 10 years, which may have been due to a larger emphasis on directly applicable research, but there is little doubt this avenue will be further explored in the future.

Models may teach us more about the general reaction pattern of the equine back, but are less suitable for use in individual cases. In recent years, inertial motion unit (IMU) technology has taken a great leap. The advantage of IMUs is their easy applicability, making them very well suited for measurements outside the lab under real field conditions. Much of the work in recent years has focused on asymmetry measurements and use for lameness detection and quantification [78]. Specific use for the quantification of back motion has been limited thus far. In a study that compared (gold standard) motion capture with IMUs to quantify spinal motion, IMUs showed acceptable accuracy and good consistency for back movement. However, the small lateral bending ROM meant that changes <25% in ROM went undetected [79]. The relatively small amplitude of spinal rotations and the strong mutual influence of especially lateral bending and axial rotation may make IMU technology not the best option to capture spinal motion.

Combining data generated by the capture of back kinematics with data from other new technologies, such as saddle pressure measurement devices [80], may allow for the monitoring of subtle changes in the motion pattern of the equine athlete. Such an individualised monitoring programme, which may include other aspects of health and soundness as well, may lead to the early detection of abnormalities and hence permit timely and adequate preventive measures. In man, such an individualised approach to peculiarities of gait [81] or to the adaptation of gait to, for instance, special shoes [82] is not uncommon. Pattern recognition has been applied to horse–rider interaction as well [83]. These coaching and monitoring programmes for performance horses will never be a substitute for good horsemanship. However, they may support the good horseman in his or her decisions and they may be of help in the frequent cases of bad horsemanship, thus promoting the well-being of the horse for the benefit of the horse itself and its users.

References

1 Van Weeren, P.R. History of locomotor research. In: Back, W. and Clayton, H.M. (eds), *Equine Locomotion*, 2nd edn, pp. 1–30. London: Saunders Elsevier, 2013, pp. 1–30.

2 Slijper, E.J. Comparative biologic-anatomical investigations on the vertebral column and spinal musculature of mammals. *Proceedings of K. Ned. Acad. Wetensch.* 1946; **42**:1–128.

3 Bergmann, C. Über die Verhältnisse der Wärme-Ökonomie der Thiere zu ihrer Grösse. *Göttinger Studien* 1847; **3**:595–708.

4 Krüger, W. Über Schwingungen der Wirbelsäule – Insbesondere der Wirbelbrücke- des Pferdes Während der Bewegung. *Berl. Münchn. Tierärztl. Wschr.* 1939; **13**:129–133.

5 Zschokke, E. *Untersuchungen über das Verhältnis der Knochenbildung zur Statik und Mechanik des Vertebraten-skelettes.* Zürich: Orell Fusli, 1892.

6 Barthez, P.J. *Nouvelle Mécanique des Mouvements de l'Homme et des Animaux.* Paris: Carcassonne, 1798.

7 Koch, T. *Lehrbuch der Veterinär-Anatomie,* Bd. I: Bewegungsapparat. Jena: VEB Gustav Fischer Verlag, 1970, pp. 281–334.

8 Jeffcot, L.B. and Dalin, G. Natural rigidity of the horse's backbone. *Equine Veterinary Journal* 1980; **12**:101–108.

9 Townsend, H.G., Leach, D. and Fretz, P.B. Kinematics of the equine thoracolumbar spine. *Equine Veterinary Journal* 1983; **15**:117–122.

10 Townsend, H.G. and Leach, D. Relationship between intervertebral joint morphology and mobility in the equine thoracolumbar spine. *Equine Veterinary Journal* 1984; **16**:461–465.

11 Denoix, J.M. Kinematics of the thoracolumbar spine in the horse during dorsoventral movements: a preliminary report. In: Gillespie, J.R. and Robinson, N.E. (eds), *Proceedings of the 2nd International Conference on Equine Exercise and Physiology*, Davis, CA: ICEEP Publications, 1987, pp. 607–614.

12 Denoix, J.M. Aspects fonctionnels des régions lombo-sacrale et sacro-iliaque du cheval. *Pract. Vet. Equine* 1992; **24**:13–21.

13 Degueurce, C., Chateau, H. and Denoix, J.M. *In vitro* assessment of the sacroiliac joint in the horse. *Equine Veterinary Journal* 2004; **36**:694–698.

14 Goff, L.M., Jasiewicz, J., Jeffcott, L.B. et al. Movement between the equine ilium and sacrum: *in vivo* and *in vitro* studies. *Equine Veterinary Journal* 2006; Suppl., **36**:457–461.

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

16 Audigié, F., Pourcelot, P., Degeurce, C., Denoix, J.M. and Geiger, D. Kinematics of the equine back: flexion-extension movements in sound trotting horses. *Equine Veterinary Journal* 1999; Suppl., **30**:210–213.

17 Pourcelot, P., Audigié, F., Degueurce, C., Denoix, J.M. and Geiger, D. Kinematics of the equine back: a method to study the thoracolumber flexion–extension movements at the trot. *Veterinary Research* 1998; **29**:519–525.

18 Tokuriki, M., Nakada, A., and Aoki, O. Electromyographic activity of trunk muscles in the horse during locomotion and synaptic connections of neurons of trunk muscles in the cat. In: *Proceedings of First (ESB) Workshop on Animal Locomotion*, Utrecht, the Netherlands, 1991, p. 36.

19 Licka, T.F., Peham, C. and Frey, A. Electromyographic activity of the longissimus dorsi muscles in horses during trotting on a treadmill. *American Journal of Veterinary Research* 2004; **65**:155–158.

20 Licka, T. and Peham, C. An objective method for evaluating the flexibility of the back of standing horses. *Equine Veterinary Journal* 1998; **30**:412–415.

21 Peham, C., Frey, A., Lickla, T. and Scheidl, M. Evaluation of the EMG activity of the long back muscle during induced back movements at stance. *Equine Veterinary Journal* 2001; Suppl., **33**:165–168.

22 Fick, R. Allgemeine Gelenk- und Muskelmechanik. In: von Bardeleben, K. (ed.), *Handbuch der Anatomie des Menschen*, Bd. 2, Abt. 1, Teil 2. Jena, 1910.

23 Denoix, J.M. Spinal biomechanics and functional anatomy. *Veterinary Clinics of North America: Equine Practice* 1999; **15**:27–60.

24 Haussler, K.K., Bertram, J.A.E., Gellman, K. and Hermanson, J.W. Dynamic analysis of *in vivo* segmental spinal motion: an instrumentation strategy. *Veterinary Comp. Orthopaedics and Traumatology* 2000; **13**:9–17.

25 Haussler, K.K., Bertram, J.E.A., Gellman, K. and Hermanson, J.W. Segmental *in vivo* vertebral kinematics at the walk, trot and canter: a preliminary study. *Equine Veterinary Journal* 2001; Suppl., **33**:160–164.

26 Faber, M.J., Schamhardt, H.C., van Weeren, P.R. et al. Basic three-dimensional kinematics of the vertebral column of horses walking on a treadmill. *American Journal of Veterinary Research* 2000; **61**:399–406.

27 Faber, M., Schamhardt, H.C. and van Weeren, P.R. Determination of 3D spinal kinematics without defining a local vertebral co-ordinate system. *Journal of Biomechanics* 1999; **32**:1355–1358.

28 Faber, M.J., Johnston, C., Schamhardt, H.C. et al. Basic three-dimensional kinematics of the vertebral column of horses trotting on a treadmill. *American Journal of Veterinary Research* 2001; **62**:757–764.

29 Faber, M.J., Schamhardt, H.C., van Weeren, P.R. and Barneveld, A. Methodology and validity of assessing kinematics of the thoracolumbar vertebral column in horses based on skin-fixated markers. *American Journal of Veterinary Research* 2001; **62**:301–306.

30 Faber, M.J., Johnston, C., Schamhardt, H.C. et al. Three-dimensional kinematics of the equine spine during canter. *Equine Veterinary Journal* 2001; Suppl., **33**,145–149.

31 Faber, M.J., Johnston, C., van Weeren, P.R. and Barneveld, A. Repeatability of back kinematics in horses during treadmill locomotion. *Equine Veterinary Journal* 2002; **34**:235–241.

32 Johnston, C., Holm, K., Faber, M. et al. Effect of conformational aspects on the movement of the equine back. *Equine Veterinary Journal* 2002; Suppl., **34**:314–318.

33 Johnston, C., Roethlisberger-Holm, K., Erichsen, C., Eksell, P. and Drevemo, S. Kinematic evaluation of the back in fully functioning riding horses. *Equine Veterinary Journal* 2004; **36**:495–498.

34 Faber, M., van Weeren, P.R., Scheepers, M. and Barneveld, A. Long-term follow-up of manipulative treatment in a horse with back problems. *Journal of Veterinary Medicine A. Physiology and Pathology in Clinical Medicine* 2003; **50**:241–245.

35 Jeffcott, L.B. Back problems in the horse – A look at past, present and future progress. *Equine Veterinary Journal* 1979; **11**:129–136.

36 Haussler, K.K., Hill, A.E., Puttlitz, C.M. and McIlwraith, C.W. Effects of vertebral mobilization and manipulation on kinematics of the thoracolumbar region. *American Journal of Veterinary Research* 2007; **68**:508–516.

37 Sullivan, K.A., Hill, A.E. and Haussler, K.K. The effects of chiropractic, massage and phenylbutazone on spinal mechanical nociceptive thresholds in horses without clinical signs. *Equine Veterinary Journal* 2008; **40**:14–20.

38 Haussler, K.K., Martin, C.E. and Hill, A.E. Efficacy of spinal manipulation and mobilisation on trunk flexibility and stiffness in horses: a randomised clinical trial. *Equine Veterinary Journal* 2010, November; Suppl., **38**:695–702.

39 Gómez Álvarez, C.B., l'Ami, J.J., Moffatt, D., Back, W. and van Weeren, P.R. Effect of chiropractic manipulations on the kinematics of back and limbs in horses with clinically diagnosed back problems. *Equine Veterinary Journal* 2008; **40**:153–159.

40 Mooij, M.J., Jans, W., den Heijer, G.J., de Pater, M. and Back, W. Biomechanical responses of the back of riding horses to water treadmill exercise. *Veterinary Journal* 2013, December; **198**(1): e120–3.

41 Clayton, H.M., Kaiser, L.J., Lavagnino, M. and Stubbs, N.C. Dynamic mobilisations in cervical flexion: Effects on intervertebral angulations. *Equine Veterinary Journal* 2010; Suppl., **38**:688–694.

42 Clayton, H.M., Kaiser, L.J., Lavagnino, M. and Stubbs, N.C. Evaluation of intersegmental vertebral motion during performance of dynamic mobilization exercises in cervical lateral bending in horses. *American Journal of Veterinary Research* 2012; **73**:1153–1159.

43 Haussler, K.K. and Erb, H.N. Mechanical nociceptive thresholds in the axial skeleton of horses. *Equine Veterinary Journal* 2006; **38**:70–75.

44 Haussler, K.K. and Erb, H.N. Pressure algometry for the detection of induced back pain in horses: A preliminary study. *Equine Veterinary Journal* 2006; **38**:76–81.

45 Wennerstrand, J., Johnston, C., Roethlisberger-Holm, K. et al. Kinematic evaluation of the back in the sport horse with back pain. *Equine Veterinary Journal* 2004; **36**:707–711.

46 Jeffcott, L.B. Disorders of the thoracolumbar spine of the horse – A survey of 443 cases. *Equine Veterinary Journal* 1980; **12**:197–210.

47 Roethlisberger Holm, K., Wennerstrand, J., Lagerquist, U., Eksell, P. and Johnston, C. Effect of local analgesia on movement of the equine back. *Equine Veterinary Journal* 2006; **38**:65–69.

48 San Juan, J.G., Yaggie, J.A., Levy, S.S. et al. Effects of pelvic stabilization on lumbar muscle activity during dynamic exercise. *Journal of Strength. Cond. Research* 2005; **19**:903–907.

49 Stubbs, N.C., Hodges, P.W. Jeffcott, L.B. et al. Functional anatomy of the caudal thoracolumbar and lumbosacral spine in the horse. *Equine Veterinary Journal* 2006; Suppl., **36**:393–399.

50 Landman, M.A.A.M., de Blaauw, J.A., van Weeren, P.R. and Hofland, L.J. Lameness prevalence in horses with back problems compared to a control population: a field study. *Veterinary Records* 2004; **155**:165–168.

51 Dyson, S. The interrelationships between back pain and lameness: A diagnostic challenge. *Proceedings of the Congress on British Equine Veterinary Association* 2005; **44**:137–138.

52 Jeffcott, L.B., Dalin, G., Drevemo, S. et al. Effect of induced back pain on gait and performance of trotting horses. *Equine Veterinary Journal* 1982; **14**:129–133.

53 Wennerstrand, J., Gómez Alvarez, C.B., Meulenbelt, R. et al. Spinal kinematics in horses with induced back pain. *Veterinary Comparative Orthopaedics and Traumatology* 2009; **22**:448–454.

54 Buchner, H., Savelberg, H., Schamhardt, H. and Barneveld, A. Head and trunk movement adaptations in horses with experimentally induced fore- or hind limb lameness. *Equine Veterinary Journal* 1996; **28**:71–76.

55 Stashak, T.S. Examination for lameness. In: Stashak, T.S. (ed.), *Adams' Lameness in Horses*, 4th edn. Baltimore, MD: Lippincott, Williams & Wilkins, 2002, p. 122.

56 Gómez Álvarez, C.B., Wennerstrand, J. Bobbert, M.F. et al. The effect of induced forelimb lameness on the thoracolumbar kinematics in riding horses. *Equine Veterinary Journal* 2007; **39**:197–201.

57 Gómez Álvarez C.B., Bobbert, M.F., Lamers, L. et al. The effect of induced hindlimb lameness on thoracolumbar kinematics during treadmill locomotion. *Equine Veterinary Journal* 2008; **40**: 147–152.

58 Santamaría, S. From foal to performer: Development of the jumping technique and the effect of early training. Thesis, Utrecht University, 2004.

59 Santamaría, S., Bobbert, M.F., Back, W., Barneveld, A. and van Weeren, P.R. Evaluation of consistency of jumping technique in horses between the ages of 6 months and 4 years. *American Journal of Veterinary Research* 2004; **65**:945–990.

60 Bobbert, M.F., Santamaría, S., van Weeren, P.R., Back, W. and Barneveld, A. Can jumping capacity of adult show jumping horses be predicted on the basis of submaximal free jumps at foal age? A longitudinal study. *Veterinary Journal* 2005; **170**:212–221.

61 De Cocq, P., van Weeren, P.R. and Back, W. Effects of girth, saddle and weight on movements of the horse. *Equine Veterinary Journal* 2004; **36**:758–763.

62 Rhodin, M., Johnston, C., Holm, K.R., Wennerstrand, J. and Drevemo, S. The influence of head and neck position on kinematics of the back in riding horses at the walk and trot. *Equine Veterinary Journal* 2005; **37**:7–11.

63 Gómez Álvarez, C.B., Rhodin, M., Bobbert, M.F. et al. The effect of head and neck position on the thoracolumbar kinematics in the unridden horse. *Equine Veterinary Journal* 2006; Suppl., **36**:445–451.

64 Decarpentry, A. *Academic Equitation*. (Translated from the 2nd revised edn of *Equitation Académique*). London: J.A. Allen & Co. Ltd, 1971.

65 Meyer, H. Rollkur. *St. Georg* 1992; **11**,70–73.

66 Balkenhol, K., Müller, H., Plewa, M. and Heuschmann, G. Zur Entfaltung kommen – Statt zur Brust genommen. *Reiter Revue* 2003; **46**(2):46–51.

67 Janssen, S. Zur Brust genommen. *Reiter Revue* 2003; **46**(2):41–45.

68 Schrijer, S. and van Weeren, P.R. Auf dem falschen Rücken ausgetragen. *Reiter Revue* 2003; **46**(7):13–15.

69 Rhodin, M., Gómez Alvarez, C.B., Byström, A. et al. The effect of different head and neck positions on the caudal back and hindlimb kinematics in the elite dressage horse at trot. *Equine Veterinary Journal* 2009; **41**:274–279.

70 Cassiat, G., Pourcelot, P., Tavernier, L. et al. Influence of individual competition level on back kinematics of horses jumping a vertical fence. *Equine Veterinary Journal* 2004; **36**:748–753.

71 Robert, C., Audigié, F., Valette, J.P., Pourcelot, P. and Denoix, J.-M. Effects of treadmill speed on the mechanics of the back in the trotting saddlehorse. *Equine Veterinary Journal* 2001; Suppl., **33**:154–159.

72 Keegan, K.G., Arafat, S., Skubic, M. et al. Detection of spinal ataxia in horses using fuzzy clustering of body position uncertainty. *Equine Veterinary Journal* 2004; **36**:712–717.

73 Van Weeren, P.R. The clinical applicability of automated gait analysis systems. *Equine Veterinary Journal* 2002; **34**:218–219.

74 Peham, C. and Schobesberger, H. Influence of the load of a rider or of a region with increased stiffness on the equine back: A modelling study. *Equine Veterinary Journal* 2004; **37**:703–705.

75 Peham, C. and Schobesberger, H. A novel method to estimate the stiffness of the equine back. *Journal of Biomechanics* 2006; **39**:2845–2849.

76 Schlacher, C., Peham, C., Licka, T. and Schobesberger, H. Determination of the stiffness of the equine spine. *Equine Veterinary Journal* 2004; **36**:699–702.

77 Groesel, M., Zsoldos, R.R., Kotschwar, A., Gfoehler, M. and Peham, C. A preliminary

model study of the equine back including activity of longissimus dorsi muscle. *Equine Veterinary Journal* 2010; Suppl., **38**:401–406.

78 Keegan, K.G., Kramer, J., Yonezawa, Y. et al. Assessment of repeatability of a wireless, inertial sensor-based lameness evaluation system for horses. *American Journal of Veterinary Research* 2011; **72**:1156–1163.

79 Warner, S.M., Koch, T.O. and Pfau, T. Inertial sensors for assessment of back movement in horses during locomotion over ground. *Equine Veterinary Journal* 2010; Suppl., **38**:417–424.

80 Von Rechenberg, B. Saddle evaluation; poor fit contributing to back problems in horses. In: Auer, J.A. and Stick, J.A. (eds), *Equine Surgery*, 3rd edn. St Louis, MO: Saunders, 2006, pp. 963–971.

81 Schöllhorn, W.I., Nigg, B.M., Stefanshyn, D. and Liu, W. Identification of individual walking patterns using time discrete and time continuous data sets. *Gait Posture* 2002; **15**:180–186.

82 Nigg, B.M., Khan, A., Fisher, V. and Stefanshyn, D. Effect of shoe insert construction on foot and leg movement. *Medical Science and Sport Exercise* 1998; **30**:550–555.

83 Schöllhorn, W.I., Peham, C., Licka, T.F. and Scheidl, M. A pattern recognition approach for the quantification of horse and rider interactions. *Equine Veterinary Journal* 2006; Suppl., **36**:400–405.