The biomechanical interaction between vertebral column and limbs in the horse: a kinematical study

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Cover illustration: Adapted from: Giovanni Borelli (1680), *De motu animalium*, pars prima. Roma.

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The biomechanical interaction between vertebral column and limbs in the horse: a kinematical study

De biomechanische interactie tussen wervelkolom en ledematen van het paard: een kinematische studie

(met een samenvatting in het Nederlands)

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Co-promotoren:	dr. W. Back dr. M. F. Bobbert dr. C. Johnston

About the cover illustration:

“De Motu Animalium seemingly constitutes the very first treatise on biomechanics. The author, Giovanni Alfonso Borelli (1608-1679), was professor of mathematics in Pisa, where he worked with Malighi who was professor of theoretical medicine and focused Borelli's interest on the movements of living creatures. The work consists of two parts. In the first part Borelli analyses the action of the muscles, the movements of the limbs, and the activities of man and animals, including skating, running, jumping, swimming and flying. The second part deals with what is now called physiology, considered from the point of view of a mechanist: heart, blood circulation, breathing, separation of urine from blood in the kidneys, liver function, reproduction, fatigue, thirst, hunger, fever, and so on. The book shows Borelli to be a genial precursor. He expresses his opinion as a mathematician on problems which afterwards further stimulated the curiosity and endeavors of many generations of researchers (Maquet, 1989)”.

Contents

Chapter 1

General introduction

Introduction

Biomechanics is the study of the mechanics of a living body, and includes kinematics (motion) and kinetics (forces) (Fung 1993). Force and motion can be seen as the product of the musculoskeletal system and are in fact determinants of athletic performance in virtually all equestrian disciplines. Therefore, it may be not surprising that musculoskeletal disorders with subsequent impairment of normal biomechanical function account for the majority of the cases of poor performance in horses (Ross and Dyson 2003). The most common disorder is lameness, but probably the most controversial and poorly understood is back dysfunction.

The thoracolumbar vertebral column, as bony basis of the back, forms part of the axial skeleton that bridges the gap between the limbs. There is a complex and intricate relationship between the biomechanics of the axial and appendicular skeleton. Maintaining an appropriate balance in this relationship is essential for correct locomotion and maximal athletic performance. However, relatively little is known about this relationship and about the mutual effects of dysfunction of one of the components.

Insight into the effects of back pain on one hand and lameness on the other on body mechanics will help us expand our understanding of the pathogenesis of these common orthopaedic ailments, improve diagnosis by identifying problems as primary or secondary, and better treat or prevent these disorders.

Anatomy and biomechanical concepts of the vertebral column

The vertebral column has important roles in locomotion. It accounts for weight bearing and provides soft tissue attachment sites, connects fore and hindquarters, and lends flexibility to the axial skeleton.

The equine vertebral column consists of 7 cervical, 18 thoracic, 5-6 lumbar, 5 sacral and 15-18 caudal vertebrae, which are strongly interconnected by joints, ligaments and muscles providing stability and motion. The column is organized in structural and functional segmental units formed by pairs of consecutive vertebrae. Each unit has bilateral dorsal synovial joints and an axial fibrocartilaginous joint with a thick intervertebral disk between the vertebral bodies. Each of these articulations only allows for subtle movements, but together they give the entire vertebral column a significant range of motion (Fig. 1.1).

The segmental motion is limited by the vertebral processes of each group of vertebrae. The thoracic back has mainly lateral motion due to the long spinous processes, which limit flexion-extension; the lumbar back offers mainly vertical motion (flexion-extension) due to the long and inter-articulated transverse processes; the sacral vertebrae are fused into one sacral bone that has a limited range of motion with respect to its neighbouring structures (ilium, last lumbar and first caudal vertebra). The cervical vertebrae have much freedom of movement and the first one, the atlas, articulates with the condyles of the occipital bone, providing great mobility to the cranium. The thoracic vertebrae also possess costal facet joints through which they articulate with the ribs, allowing interaction with the thorax.

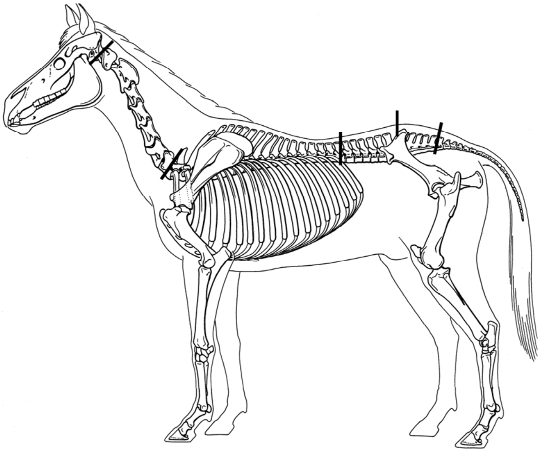

Figure 1.1. Skeleton of the horse: straight lines indicate the division of the vertebral column in cervical, thoracic, lumbar, sacral and coxigeal vertebrae (Adapted from: Dyce *et al* (2002) Textbook of veterinary anatomy. 3rd Ed., Saunders, Philadelphia).

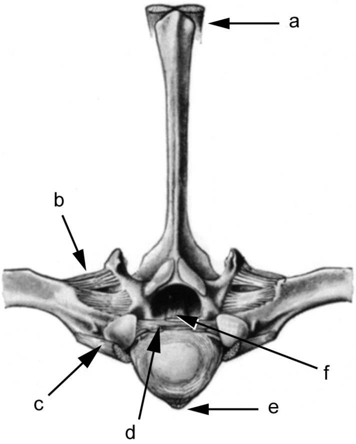

Figure 1.2. Vertebral ligaments: Cranial view of a thoracic vertebra articulating with the corresponding rib pair in the horse, a) supraspinal ligament; b), c) and d) costo-vertebral ligaments; e) ventral longitudinal ligament and f) dorsal longitudinal ligament. (Adapted from: Nickel *et al* (1986) The anatomy of the domestic animals: the locomotor system of the domestic animals. Vol 1. 5th Ed., Springer-Verlag Inc., New York).

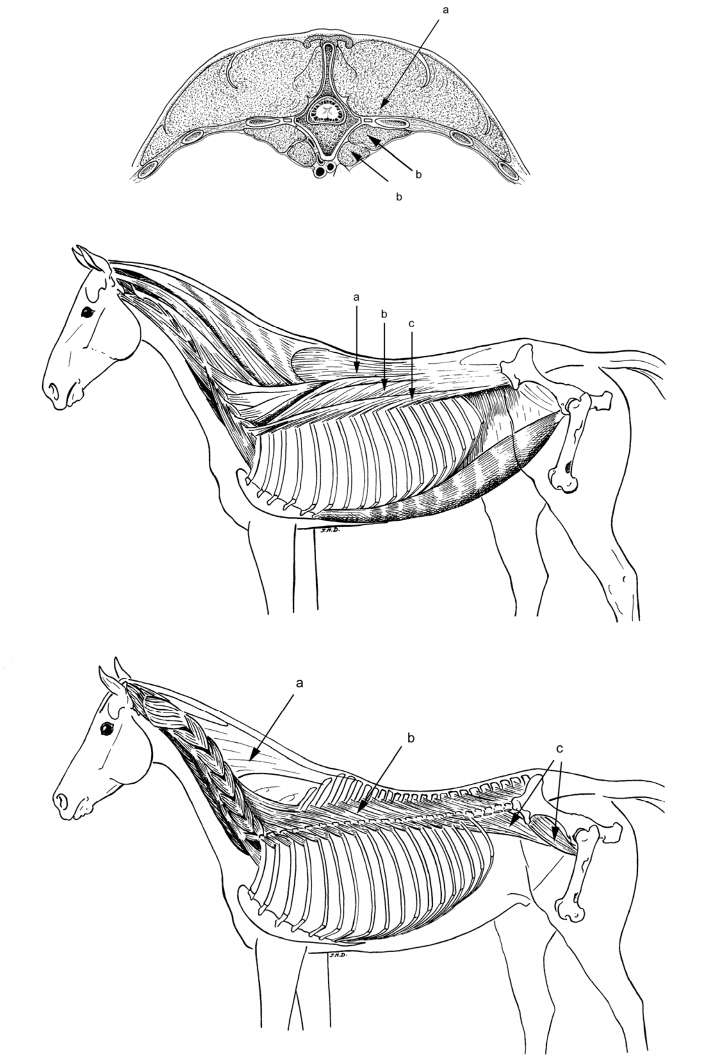

Figure 1.3 Vertebral muscles of the horse. Top figure: Transversal section of vertebral muscles at the level of lumbar vertebrae; a) epaxial muscles (iliocostalis, longissimus dorsi and spinalis), and b) hypaxial muscles (psoas major and psoas minor) (Adapted from: Dyce *et al* (2002) Textbook of veterinary anatomy. 3rd Ed., Saunders, Philadelphia). Middle figure: Longitudinal view of the superficial muscles of the back; a) spinalis, b) longissimus and c) iliocostal. Low figure: deep muscles of the back and nuchal ligament; a) nuchal ligament, b) multifidus muscle and c) iliopsoas muscle (psoas major and iliacus) (Adapted from: Denoix and Pailloux (2001) Physical therapy and massage for the horse. 2nd Ed., Manson Publishing, London).

Various short ligaments connect two consecutive vertebrae supplying stability to the segment, while longitudinal ligaments join all or most vertebrae, restricting motion of the entire thoracolumbar column (Fig. 1.2). Intrinsic vertebral muscles are divided into two groups: epaxial and hypaxial. The first group is situated dorsal to the transverse vertebral processes provoking back extension when contracting. These include *iliocostalis*, *longissimus dorsi*, *multifidus* and *spinalis* muscles. The second group is situated ventral to the transverse vertebral processes provoking back flexion; the major constituents of this group are *psoas major*, *psoas minor* and *iliacus* muscles. Both groups of muscles work together to maintain stability and generate vertebral motion (Fig. 1.3).

The current biomechanical concept of how the back functions was proposed by Slijper (1946). This concept describes the mammalian trunk as a bow and a string, where the bow represents the thoracolumbar vertebral column and the string is the ventral part of the trunk (Fig. 1.4). The bow and string function in a dynamical balance, influenced by other structures such as the abdominal mass, the limbs and the head (and neck). The gravitational force on the abdominal mass pulls the bow down resulting in extension of the back; protraction of the forelimbs and retraction of the hindlimbs have the same effect, while retraction of the forelimbs and protraction of the hindlimbs result in back flexion. Figure 1.5 gives a schematic representation of the muscular, tendinous and bony structures interacting in the bow-and-string model.

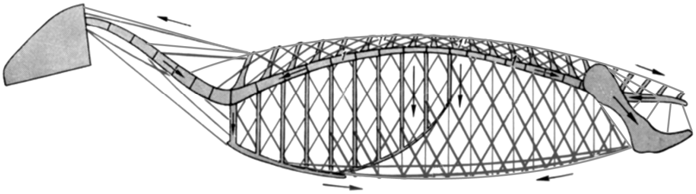

Figure 1.4. Bow and string model according to Slijper (1946) (Modified from: Nickel et al (1986) The anatomy of the domestic animals: the locomotor system of the domestic animals. Vol1. 5th Ed., Springer-Verlag Inc., New York).

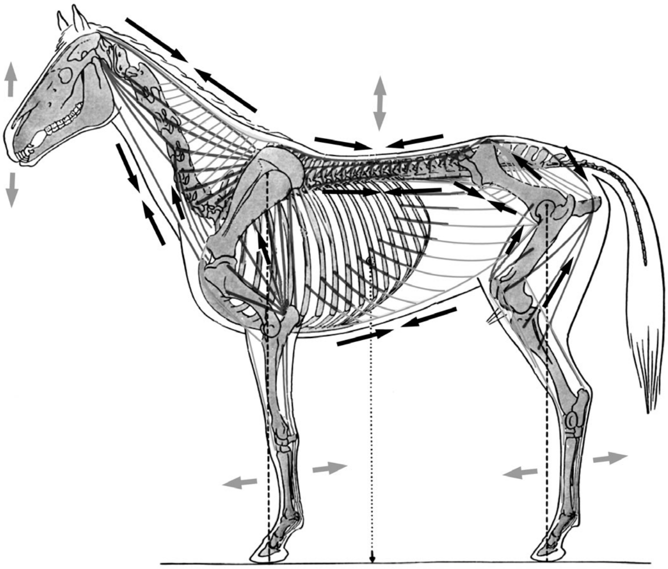

Figure 1.5. Muscular, tendinous and bony structures interacting in the bow-and-string model: black arrows represent the pulling direction of the tendons and direction of muscle contraction, and grey arrows represent the movement of the head, back and limbs in one plane (Adapted from: Nickel et al (1986) The anatomy of the domestic animals: the locomotor system of the domestic animals. Vol1. 5th Ed., Springer-Verlag Inc., New York).

In vivo vertebral kinematics and gait analysis systems

Research into equine vertebral kinematics started a few decades ago, when back problems were increasingly recognised as a serious issue in equine health and gait analysis systems came onto the market that allowed for detailed analysis of equine locomotion.

Clinical examination has always been, and still is, the method of choice for the evaluation of gait in the horse. Semi-quantitative scales are widely used to score lameness (Stashak 2002) but, although intra-observer variability is known to be remarkably low, these systems are subjective and not very suitable for the assessment of back movement, where significant and relevant changes in motion can be very minor and not well perceptible for the human eye. Gait analysis systems allow for the detailed examination of kinetics and kinematics during stance or locomotion. Kinematic analyses are carried out by using video or opto-electronic devices with specially designed software permitting the 3D analysis of markers located on selected landmarks. Kinetics is generally studied by using force plates/shoes, strain gauges and accelerometers. Recently, calculation of vertical limb forces from kinematics has been developed (Bobbert *et al*. 2007; McGuigan and Wilson 2003). This approach allows estimating the forces when kinetic devices are not available or circumstances do not permit the use of such devices.

One of the most commonly used marker types in kinematical studies in horses is the passive skin marker, which is glued directly to the skin over an underlying bony structure that serves as a landmark. The discrepancy between the movement of the skin marker and the underlying bony structure, the so-called skin displacement artefact, is a source of error that has been well recognised in human (Taylor *et al*. 2005) and equine gait analysis (van den Bogert *et al*. 1990; van Weeren and Barneveld 1986). In the horse a computer programme (Bacckin®[1]) has been developed based on invasively collected data (Faber *et al*. 1999, 2000; Johnston *et al*. 2002) that can calculate thoracolumbar angular motion patterns from skin marker-derived data. The programme thereby automatically corrects for the skin displacement artefact, although the data for lateral bending still have to be interpreted with caution.

Computerized gait analysis systems have been used to study vertebral motion of healthy horses (Audigie *et al*. 1999; Faber *et al*. 1999, 2000, 2001a, b, c, 2002; Haussler *et al*. 2000, 2001; Johnston *et al*. 2002, 2004; Licka and Peham 1998; Licka *et al*. 2001a, b; Pourcelot *et al*. 1998). These studies describe the movement patterns and ranges of motion of various segments of the vertebral column. The basic movements of the vertebral column are flexion-extension (FE) in the sagittal plane, which is equivalent to rotation around the transverse axis in an orthogonal coordinate system; lateral bending (LB) in the horizontal plane, which is rotation around the vertical axis; and axial rotation (AR) in the transverse plane, which is the rotation around the longitudinal axis. During walk and trot, FE motion of the vertebral column has a bimodal sinusoidal pattern in one stride cycle; lateral bending and axial rotation have a single curve per stride (Faber *et al*. 2000, 2001a). As locomotion is generated in the hindquarters, there is a caudal-to-cranial time shift in the vertebral motion patterns within a stride cycle, with increasing delay towards the cranial end of the thoracolumbar spine (Faber *et al*. 2000) (Fig. 1.6).

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[1] Qualisys Medical AB, Gothenburg, Sweden.

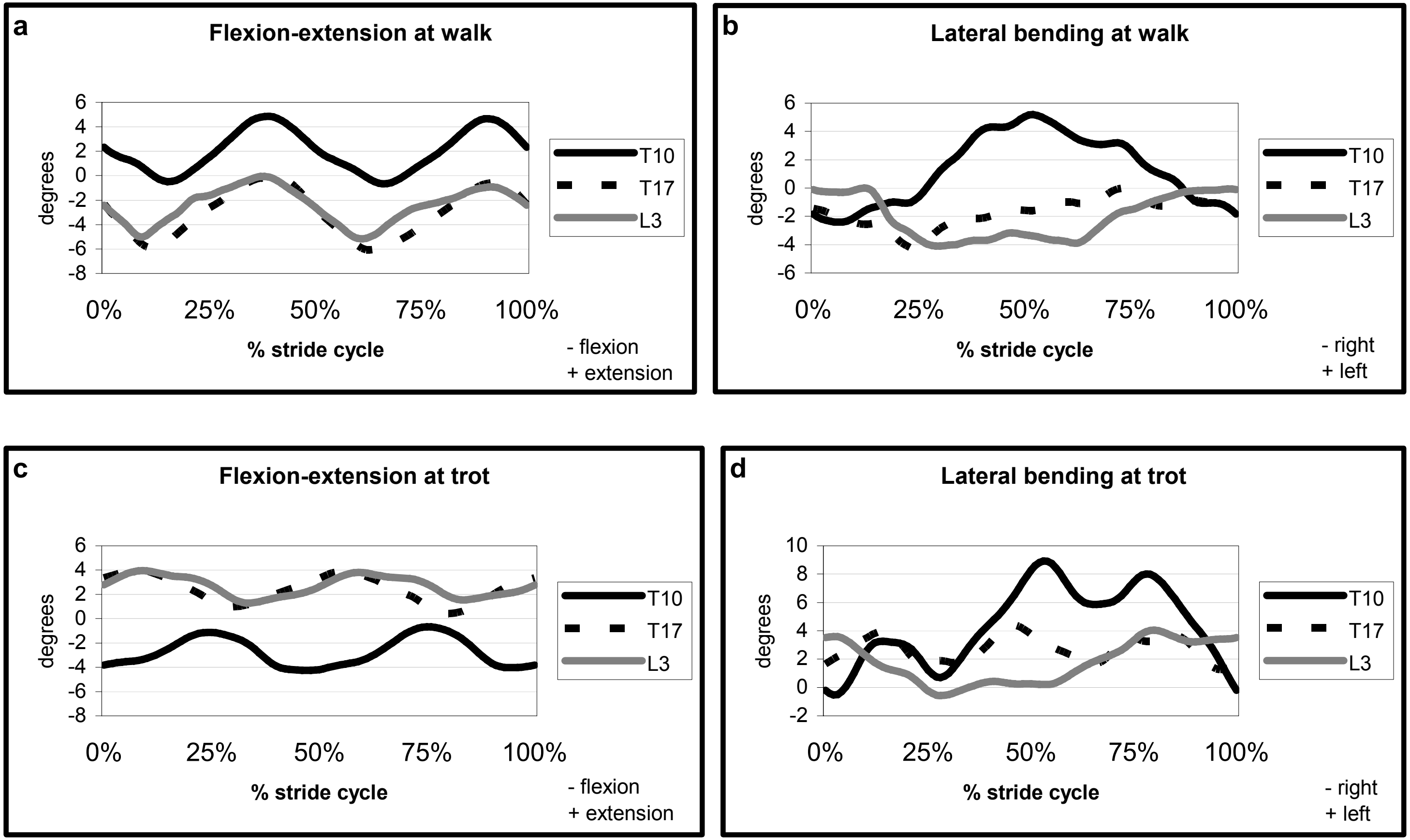

Figure 1.6. Example of angular motion pattern of three vertebral angles (T6-T10-T13, T13-T17-L1, L1-L3-L5) in one horse a) flexion-extension at walk; b) lateral bending at walk; c) flexion-extension at trot; d) lateral bending at trot.

Lameness and back pain

Musculoskeletal pain can be seen as a protective mechanism, as it gives an early warning to the individual when there is a harmful or potentially harmful process in the body (Bergman 2007). There is little discussion anymore about the similarity of pain perception in humans and animals (Livingston 1994), and there is no doubt that musculoskeletal pain has the same function in animals. Nowadays, research on pain assessment and its effects on performance is receiving extra attention as an animal welfare issue in horses. Pain can be assessed by paying attention to behavioural signs (Ashley *et al*. 2005). Lowering the head, a rigid stance and reluctance to move are non-specific behavioural indicators of pain, while indicators of limb pain are weight shifting between limbs, limb rigidity, postural alterations, lack of mobility, etc. (Ashley *et al*. 2005).

Signs of back pain are in general rather vague and unspecific and therefore of limited use in diagnosis of back pain. Normally, the main sign is poor performance and the rest of the signs are unspecific. Palpation can be performed of the superficial structures only, and sensitivity to palpation does not necessarily mean that there is a clinically relevant back problem. Attempts have been made to objectify quantify back pain in the horse. Mechanical nociceptive thresholds have been investigated in the axial skeleton of horses using an algometer by Haussler and Erb (2006a, b), but unfortunately the use of this tool is still not common practice for pain assessment by equine veterinarians.

Back problems can be due to a great diversity of causes. These can be divided into primary, secondary and alleged or apparent. Primary back pain can be located in soft tissue, vertebral bone or articulations. Secondary back pain can be due to lameness, and pelvic or neck injury (Jeffcott 1999). Minor spinal muscle soreness is frequently secondary to lameness (Marks 1999).

Understanding the relationship between back pain and lameness has always been a challenge and an important goal in equine orthopaedics (Dyson 2005). In a population of horses presented for orthopaedic problems, 26% had concurrent lameness and back pain upon palpation (Landman *et al*. 2004). Dyson (2005) reported that, in the majority of horses with primary thoracolumbar or sacroiliac pain, overt lameness was not a feature, but many horses showed restricted hindlimb propulsion, poor hindlimb engagement and a low-grade toe drag. However, apart from these clinical observations, little work has been done to investigate the relationship between back and limb motion.

There is ample kinematical work on lameness and there is especially much evidence of the effect of foot pain on linear and temporal stride parameters and angular motion patterns of the limbs (Buchner *et al*. 1995, 1996b; Galisteo *et al*. 1997); and on the motion pattern of trunk and head (Buchner *et al*. 1996a; Denoix and Audigie 2001; Keegan *et al*. 2000; Uhlir *et al*. 1997; Vorstenbosch *et al*. 1997). Moderate lameness has been reported to affect back motion also. Pourcelot *et al*. (1998) showed in a single case study that the thoracolumbar back presented less extension during the lame diagonal stance phase at trot, but increased extension during the sound diagonal stance phase at trot.

When it comes to the effect of back problems on limb motion, the situation is less clear. It was shown in an experimental study that relatively severe induced back pain provoked stiffening of the back, but affected stride parameters only marginally (Jeffcott *et al*. 1982). In natural cases, patients with back pain seem to reduce the flexion-extension motion in their backs and the axial rotational motion of the pelvis (Wennerstrand *et al*. 2004). In a recent treadmill study on horses, in which implanted pins in the dorsal spinous processes were used as a pain model and to measure vertebral motion, vertical displacement was decreased in several vertebral segments (Haussler *et al*. 2007).

Back pain affects back motion and may or may not affect limb kinematics. Pain in the limbs leads to lameness, which in fact is synonymous to alteration of limb kinematics and will affect both back motion and motion pattern of the head. An altered head motion pattern is one of the key elements in the diagnosis of (forelimb) lameness (Stashak 2002). Considering that the head is an extension of the axial skeleton, altered head motion in its turn will affect back motion to some extent. This will happen in the case of lameness, but also when head and/or neck are forced into extreme and sometimes unnatural positions as is not uncommon during training for certain equestrian disciplines such as show jumping and dressage. The total picture of the motion patterns of the head and the axial and appendicular skeleton is very complicated because of the mutual interactions between these constituting elements of the entire skeleton, which are tightly connected through bony, muscular and ligamentous links. In a sound horse, the entire system is in balance. However, if pain affects one of the elements (vertebral column, limbs, and head) the balance will be lost, affecting the entire system of interconnected motion chains. Understanding this interaction can lead to better diagnosis, treatment and prevention of back problems.

Treatment of back pain

Given the elusive and complicated character of back pain in the horse, it will be hardly surprising that there is a wide variety of treatments that are advocated in case of (presumed) equine back pain. The main objectives of all of them are pain management, and reduction of tension and inflammation.

Medical management of back pain includes the use of steroidal and non-steroidal anti-inflammatory drugs, muscle relaxants and others. Depending on the type of drug, application may be either systemically or locally at the site of any pathology such as arthrotic facet joints or places where neighbouring spinous processes make contact, the so-called “kissing spines”.

Medical treatment is very often accompanied by some kind of complementary therapy, in many cases a form of physical therapy. Physical therapy may consist of tissue stimulation by electrical, magnetic, light, ultrasound, or laser energy, or massage and/or therapeutic exercise. Acupuncture and chiropractic treatment are other commonly used complementary techniques in the management of equine back pain. The objective of physical therapy is to enhance the natural healing process of the tissue through the modulation of inflammation, tissue proliferation and remodelling (Bromiley 1999). The effects of massage are reduction of pain and tension and improvement of blood flow (Bromiley 1999). The Chinese concept of acupuncture is based on the manipulation of energy that is supposed to flow through meridians or channels, promoting tissue healing and diminishing pain (Ridgway 1999). Chiropractic care uses short-lever, high-velocity, low-amplitude, controlled thrusts applied to specific joints or tissues to induce a therapeutic response by inducing changes in joint structures, muscle function and neurological reflexes (Haussler 1999).

There is anecdotal evidence that some of these approaches, together with an appropriate tack and saddle fit, correct shoeing, rest and adequate exercise and training may improve back pain and/or help to prevent back problems, but very little scientific data are available supporting these claims for clinical effectiveness.

Purpose of the thesis

The purpose of this thesis was to improve the understanding of the biomechanical relationship between motion patterns of the axial and appendicular skeleton of the horse, using kinematical analysis. To achieve this goal, the kinematics of the back and/or limbs (including in some cases ground reaction forces derived from kinematics) were studied in horses that were experimentally exposed to either specific head and neck positions, induced lameness, induced back pain, or chiropractic treatment, all of which might influence the balance in the motion chains that lies at the basis of the concerted action of limbs and back in the horse.

Outline

In **Chapter 2** the effect of different head and neck positions on thoracolumbar kinematics is investigated. Theoretically, the position of head and neck is supposed to influence thoracolumbar vertebral kinematics (Denoix and Pailloux 2001), but this interaction has never been experimentally demonstrated in the horse. This chapter allows us to understand how and by how much the head and neck position affects back motion.

In **Chapter 3** the effect of subtle forelimb lameness on vertebral kinematics is the subject of study and in **Chapter 4** a similar approach is used to investigate the effect of subtle hindlimb lameness. It is known that moderate or severe lameness changes the movement of the head and neck (or pelvis). A moderate or severe lameness can therefore be supposed to have some effect on thoracolumbar kinematics as well. However, what about the claim that subtle or even subclinical lameness may be implicated in the pathogenesis of back pain? Does such a very subtle and hardly perceptible lameness cause any changes at all in thoracolumbar kinematic patterns that might help to support this claim? Chapters 3 and 4 answer this question.

In **Chapters 5 and 6** the focus shifts from the limbs to the back. Chapter 5 studies the effect of induced back pain on limb kinematics. If changes in head (and neck) motion affect spinal kinematics and changes in limb kinematics can be found to affect back motion, do pain-induced changes in back motion affect limb motion in a comparable way? In Chapter 6 the effect of induced back pain on vertebral kinematics is addressed. Can the effect of induced back pain on thoracolumbar kinematics be related to the anatomical location of the disorder? And how do back kinematics develop over time in response to a single-event injury?

In **Chapter 7** the effect of chiropractic treatment is chosen as an example of a complementary treatment modality of back pain. The knowledge and insights emanating from the previous six chapters are used to try to understand how the biomechanical changes in one element of the axial and appendicular skeleton may affect the others and to answer the question whether treating back pain reverses the biomechanical changes in the limbs and the back itself.

Chapter 8 is a general discussion that integrates the findings from chapters 2-7 and puts them in perspective. The chapter evaluates to what extent this thesis has succeeded in improving our understanding of the complex interactions between limbs and back function in equine biomechanics. It further focuses on the clinical and societal relevance of certain findings and identifies areas in which further research seems most urgent.

Chapter 2

The effect of head and neck position on the thoracolumbar kinematics in the unridden horse

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Summary

Reasons for performing the study: In many equestrian activities a specific position of head and/or neck is required that is dissimilar to the natural position. There is a lot of controversy about the effects of these positions on locomotion pattern, but little quantitative data are available.
Objectives: To quantify the effects of 5 different head and neck positions on thoracolumbar kinematics of the horse.
Methods: Kinematics of 7 high level dressage horses was measured walking and trotting on an instrumented treadmill with the head and neck in the following positions: 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. HNP1 was a speed-matched control (head and neck unrestrained).
Results: The head and neck positions affected only the flexion-extension motion ($p<0.05$). The positions in which the neck was extended (HNP2, 3, 5) increased extension in the anterior thoracic region, but increased flexion in the posterior thoracic and lumbar region. For HNP4 the pattern was the opposite. Positions 2, 3 and 5 reduced the flexion-extension range of motion (ROM) while HNP4 increased it. HNP5 was the only position that negatively affected intravertebral pattern symmetry and reduced hind limb protraction ($p<0.05$). The stride length was significantly reduced at walk in positions 2, 3, 4 and 5 ($p<0.05$).
Conclusions: There is a significant influence of head/neck position on back kinematics. Elevated head and neck induce extension in the thoracic region and flexion in the lumbar region; besides reducing the sagittal range of motion. Lowered head and neck produces the opposite. A very high position of the head and neck seems to disturb normal kinematics.
Potential relevance: This study provides quantitative data on the effect of head/neck positions on thoracolumbar motion and may help in discussions on the ethical acceptability of some training methods.

Keywords: Back kinematics, dressage horses, head and neck positions.

Introduction

In dressage, horses are required to compete in certain positions of head and neck that do not correspond to the natural positions that the horse would assume during regular movement. This is especially obvious with respect to the position of the head and neck, which is described in the rules of the Fédération Equestre Internationale (FEI) as: “The neck should be raised, the poll high and the head slightly in front of the vertical”, implying a much more upright position than in the natural situation. Guidelines for the correct position of the head and neck in dressage have been given and discussed for ages in the equestrian literature (Cavendysh 1674, de Solleysel 1733, Lenoble du Teil 1889, Decarpentry 1971), and still continue to be a source of controversy at present times (Balkenhol *et al*. 2003; Janssen 2003). However, despite the existence of many theories, little scientific data on the effect of different head and/or neck positions on equine biomechanics exist.

Given the well-established and accepted “bow-and-string” biomechanical concept of the back in quadrupeds (Denoix 1999; Slijper 1946), an effect of the head and neck position on back kinematics can be expected. Thanks to technical advances in measuring equipment, the movement of the spine and the individual vertebrae could be studied in detail in anatomical specimens (Denoix 1987; Townsend *et al*. 1983; Townsend and Leach 1984) and in vivo (Audigié *et al*. 1999; Faber *et al*. 2000, 2001a; Haussler *et al*. 2001; Johnston *et al*. 2002, 2004; Licka *et al*. 2001a, b). Based on earlier studies (Faber *et al*. 1999, 2002, Johnston *et al*. 2002) software was developed that enabled the accurate determination of thoracolumbar kinematics based on skin markers. This software has been used in an earlier study to assess the influence of head/neck positions on the range of motion of the equine thoracolumbar spine (Rhodin *et al*. 2005). In the study by Rhodin *et al*. (2005), three different positions of the head and neck were used: free, low and high. The results of this study demonstrated the effect of head and neck position on stride variables and spinal kinematics, showing that restraining the position of the head and neck changes back kinematics and stride parameters at walk, and that a more upright position reduced the flexion-extension movement of the caudal back more than the low position. The present study aims at the evaluation of a larger number of head/neck positions, including some more extreme positions currently under discussion. Further, a more detailed analysis of thoracolumbar kinematics is pursued, which includes range of motion, vertebral angular motion patterns, intravertebral symmetry and variability, all in relation to stride and pro- and retraction angles of the hind limbs. It was hypothesised that all positions deviating from the free position would induce significant changes in thoracolumbar kinematics in the sense that more extreme positions would be characterised by a larger restriction of normal motion.

Materials and Methods

The experiment was carried out at the Equine Hospital, University of Zurich, Switzerland. The experimental protocol had been approved by the Animal Health and Welfare Commission of the canton of Zurich.

Horses

Seven Warmblood dressage horses, one competing at intermediate and six at Grand Prix levels, were used in this study. As determined by an experienced clinician, the horses were found to be sound and did not demonstrate pain or dysfunction of the back. Although not every horse had the same size, the body proportions of the different horses were similar. The horses were 6 geldings and 1 stallion, 14±4.3 years of age, with a height at the withers of 1.7±0.1 m, and a body mass of 609±62.3 kg. Beforehand, the horses had been fully accustomed to treadmill locomotion with and without a rider.

Experimental set-up

The horses were measured walking and trotting on a high-speed treadmill[1] with an integrated force measuring system (Weishaupt *et al*. 2002). The gaits were performed with six different head and neck positions. The positions were achieved using standard side reins, additional side reins connecting the bit to the girth, and a custom-made over-check; and they were evaluated by a qualified dressage judge. No tension was made in the side reins during the measurements. The positions were defined as follows (Fig. 2.1):

HNP1: Free or natural (voluntarily acquired position, unrestrained with loose reins)
HNP2: Neck raised, poll high and bridge of the nose slightly in front of the vertical
HNP3: Neck raised, poll high and bridge of the nose slightly behind the vertical
HNP4: Neck lowered and flexed, bridge of the nose considerably behind the vertical
HNP5: Neck extremely elevated and bridge of the nose considerably in front of the vertical
HNP6: Neck and head extended forward and downward

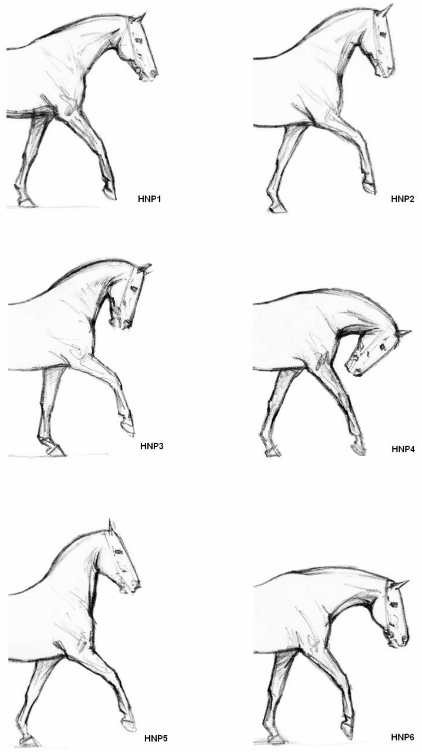

Figure 2.1. Head and neck positions (HNP). HNP1: control (head and neck unrestrained); HNP2: neck raised, bridge of the nose in front of the vertical; HNP3: as HNP2 with bridge of the nose behind the vertical; HNP4: head and neck lowered, nose behind the vertical; HNP5: head and neck in extreme high position; HNP6: head and neck forward downward.

All horses were measured at their individual preferred speed using an automated kinematic analysis system. The preferred speed was defined as the speed at which the horse moved relaxed and showed the best performance at each of the head and neck positions according to the dressage judge. As preferred speed changed with the different head/neck positions, reference measurements were made with the head and neck in free or natural position (HNP1) at the same speed as preferred by the horse for the specific head/neck position, in order to have a speed-matched control. To achieve this, a speed range was made measuring the horses in free position from 1-1.9 m/s every 0.1 m/s at walk and from 2.5-3.7 m/s every 0.2 m/s at trot.

Stride parameters were calculated from kinetic data obtained by means of the force plate system synchronized with the kinematics measurements.

Kinematic measurements

Spherical reflective 19 mm diameter markers (ProReflex[2]) were glued to the skin on the spinous processes of T6, T10, T13, T17, L1, L3, L5, and S3, both coxal tuberosities and the lateral sides of the hooves. Twelve ProReflex[2] infrared cameras were positioned around and over the treadmill. Recording took place during 10 seconds with a frame rate of 240 Hz with the horses standing square and during walk and trot with the different head/neck positions. Before the recording session, the volume required to capture full kinematics of the horse during locomotion was calibrated.

Data processing

Qualisys Track Manager software[2] was used to capture and process the data. A standard right-handed orthogonal Cartesian coordinate system was used to describe the motion of the vertebral column. In this system, the x-axis was located parallel to the treadmill in the direction of movement, the z-axis pointed upward and the y-axis was perpendicular to the plane formed by the x- and z-axes. Data captured in the square standing horse were used as a reference for the calculation of angles. Motion was described as flexion-extension (in the sagittal plane), lateral bending (in the medio-lateral plane), and pelvic axial rotation (S3 with respect to the position of the markers on the coxal tuberosities) using the BacKin[2] programme based on Faber *et al*. (1999, 2002) and Johnston *et al*. (2002). Angular motion patterns (AMP) were determined for T10, T13, T17, L1, L3 and L5 in which the vertebral angle was defined as the angle between the lines connecting the vertebra under study to adjacent marked vertebrae (e.g., the angle at T10 is the angle between the line from T10 to T6 and the line from T10 to T13). The AMP was expressed as a function of the stride cycle as determined by ground reaction force data. Positive angular displacements corresponded to clockwise rotations and negative values to counter-clockwise rotations. For the vertebral AMP of T10, T13, T17, L1, L3 and L5 a mean AMP (mAMP) and range of motion (ROM) were calculated for flexion-extension, lateral bending and, for S3, axial rotation. The ROM was defined as the difference between maximal and minimal AMP values. A correlation coefficient was calculated for each of the vertebral angular motion patterns to quantify the intra-vertebral pattern symmetry (IVPS) (Faber *et al*. 2000). Variability of ROM values was expressed as coefficient of variability (CV) to describe variation among horses, positions and strides (BHV, BPV, BSV). In addition to spinal kinematics, pro- and retraction angles were calculated for the hind limb using the markers on the left hind hoof and on S3. In this case, the maximal angle of protraction minus the maximal angle of retraction was defined as the ROM.

Data were tested for normality and analysed by paired t-test if normally distributed. If data were not normally distributed a Wilcoxon signed rank test was used. The level of significance was set at $p<0.05$.

Results

Speeds

Preferred speeds for the different conditions were 1.6±0.1 m/s for HNP2, 1.5±0.1 m/s for HNP3, 4 and 5, and 1.7±0.1 m/s for HNP6 at walk. At trot speeds were 3.2±0.1 m/s for HNP2 and 6, 3.1±0.1 m/s for HNP3, 3.0 ±0.1 m/s for HNP4 and 2.9±0.1 m/s for HNP5. The speed of the control measurements (HNP1) was not significantly different from the speed of the position they were matched with.

Angular motion patterns

Flexion-extension was the only mAMP of the back that showed changes. No significant effect on mAMP in lateral bending or axial rotation occurred in any of the positions (Fig 2.2a, b).

At walk, in HNP2, 3 and 5 there was a significant increase of extension at T10, but at T17, L1 and L3 the spine was more flexed. In contrast, in HNP4 the spine was more flexed at T10 and more extended at L5, and in HNP6 the spine was more flexed at T10 but there was no increase in extension of any of the lumbar vertebrae (Table 2.1).

At trot a similar, though somewhat less evident pattern could be observed: an increase in extension occurred at T10 for HNP2, 3 and 5; and in HNP5 an increase in flexion occurred at T17, L1 and L3. In HNP2 there was an increase in flexion at T17 and L1, and in HNP3 there was no significant change in the vertical movement of any of the thoracic or lumbar vertebrae. In HNP4 the spine was more extended at T13, T17, L1, and L5. In HNP6 there was no significant change in any of the angles (Table 2.1).

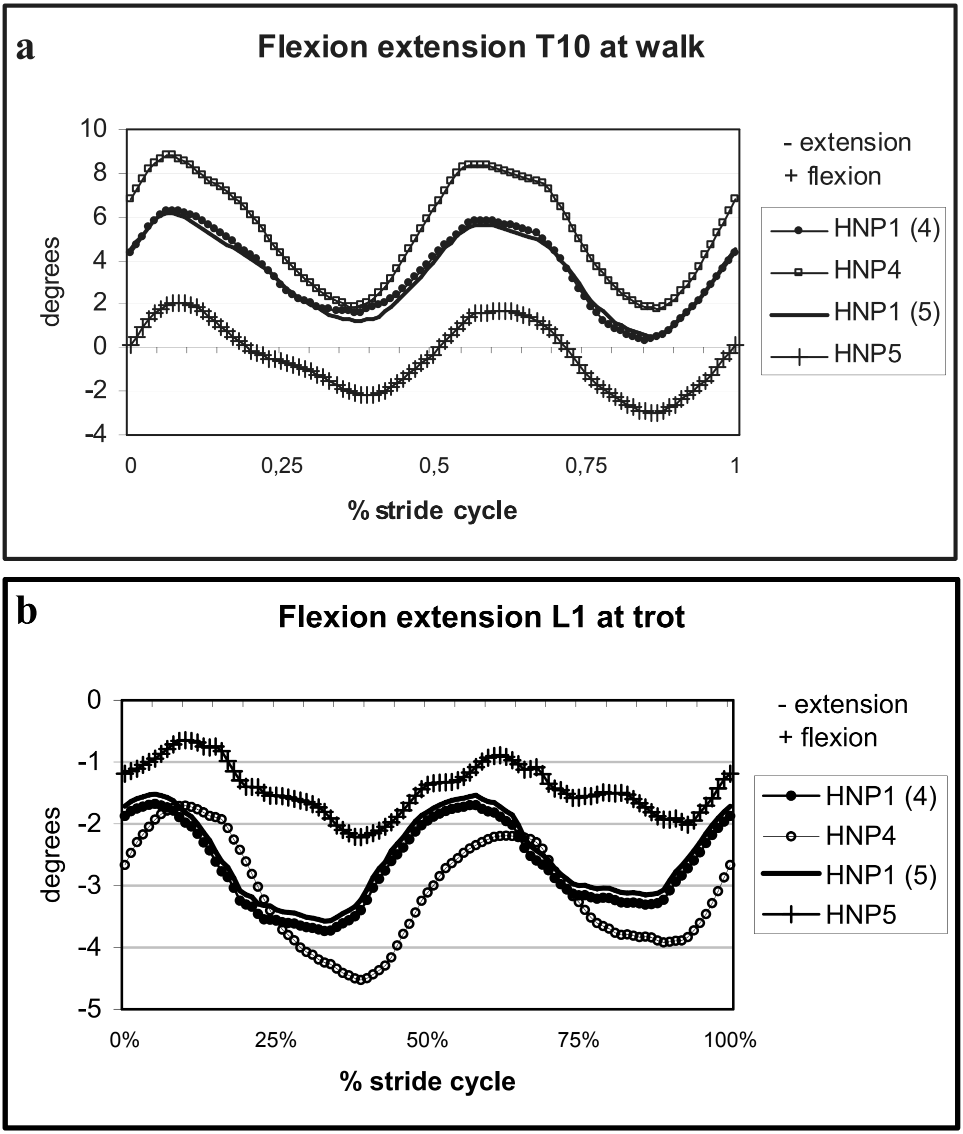

Figure 2.2. Flexion extension angular motion pattern (AMP) of one horse. a: T10 at walk, b: L1 at trot. The curves represent positions 4 (HNP4) and 5 (HNP5), and their controls (HNP1). The stride cycle is starting with the front left limb.

Range of motion

Significant changes in ROM were observed mainly in flexion-extension; only in the case of HNP5 significant changes were found in lateral bending and/or axial rotation (Table 2.2, 2.3).

At walk there were no changes at all in HNP3 and 6. In HNP2 there was a significant reduction of the flexion-extension ROM at L5. In HNP5 this was also the case, but there was also a reduction at L3 in flexion-extension ROM and a reduction in *pelvic* axial rotation ROM. In contrast, in that position lateral bending increased at T13 and T17. In HNP4 there was a significant increase in flexion-extension ROM of T10.

At trot ROM was reduced at T17 and L1 in HNP2, at T17 in HNP3, and at T10, T13 and T17 in HNP5. In the latter position there was an increase of axial rotation at S3. In HNP4 there was an increase in ROM at T10 and at all lumbar vertebrae (L1, L3 and L5). In HNP6 there was an increase ROM at T10 and T13.

Intravertebral pattern symmetry

The only position that resulted in a significant decrease in intravertebral pattern symmetry was HNP5 at walk where IVPS decreased to 84-95% for the angles at all vertebrae compared with a 96-99% symmetry range in the control measurements.

Variability

As expected, between horses variability (BHV) was higher than between positions variability (BPV), and both were higher than between strides variability (BSV). There was no influence of any of the positions on these parameters, except for a significant increase of BSV in flexion-extension of T10 and T17 at trot in HNP2 ($p<0.05$).

Pro- and retraction of the limbs

There was only one position in which there was a significant influence of head/neck position on pro- or retraction angles of the hind limbs: in HNP5 at walk, a reduction of the ROM (from 40.1±1.4° to 37.7±1.5°, $p<0.001$) occurred due to a decreased protraction.

Linear stride parameters

The stride length was significantly reduced at walk only, by 4.2% in HNP2 ($p=0.001$), 3.0% in HNP3 ($p=0.004$), 2.0% in HNP4 ($p=0.003$) and 6.1% in HNP5 ($p=0.0001$).

Table 2.1. Mean Angular motion pattern (mAMP) values for flexion-extension (mean±SD) at trot and walk at different positions of the head and neck (HNP).

Trot			HNP2	HNP3	HNP4	HNP5	HNP6
Flexion-Extension	T10	(control) Δ [%]	3.7±2.3 (5.7±2.4) -34.6% $^{\&}$	4.3±2.1 (5.8±2.3) -26.7% $^{\&}$	6.1±2.3 (5.9±2.3) 4.2%	1.6±1.6 (6.1±2.1) -73% $^{\#}$	6.5±2.3 (5.8±2.3) 10.8%
	T13	(control) Δ [%]	-0.5±1.4 (-0.3±1.8) 70.3%	-0.4±1.6 (-0.2±1.8) 82.6%	-0.7±1.7 (-0.2±1.7) 185.5% *	-0.3±1.2 (-0.2±1.8) 56.2%	-0.3±1.7 (-0.3±1.8) 6.4%
	T17	(control) Δ [%]	-2.1±1.0 (-2.4±1.1) -15% *	-2.1±1.0 (-2.4±1.1) -11.9%	-2.7±1.2 (-2.3±1.1) 15% *	-1.5±0.9 (-2.4±1.1) -37.4% $^{\#}$	-2.5±1.0 (-2.4±1.1) 1.4%
	L1	(control) Δ [%]	-2.5±0.7 (-2.9±0.9) -14.4% *	-2.6±0.8 (-2.9±0.9) -10.4%	-3.0±1.0 (-2.8±1.0) 8.1% *	-2.0±0.7 (-2.8±1.0) -29.4% $^{\&}$	-2.9±0.8 (-2.9±0.9) -1.0%
	L3	(control) Δ [%]	-2.8±0.7 (-3.1±1.0) -9.3%	-2.9±0.8 (-3.1±1.0) -5.5%	-3.1±0.9 (-3.0±1.0) 5.2%	-2.2±0.7 (-3.0±1.0) -24.4% *	-3.1±0.7 (-3.1±1.0) -0.1%
	L5	(control) Δ [%]	-1.3±1.1 (-1.4±1.2) -5.5%	-1.5±1.1 (-1.4±1.2) 2.8%	-1.6±1.1 (-1.3±1.1) 19.6% *	-1.1±1.0 (-1.3±1.1) 18.6%	-1.3±1.1 (-1.4±1.2) -7.1%
Walk			HNP2	HNP3	HNP4	HNP5	HNP6
Flexion-Extension	T10	(control) Δ [%]	1.7±2.1 (4.0±1.7) -56.2% $^{\#}$	2.6±1.7 (3.8±1.7) -33.2% $^{\&}$	5.1±2.2 (3.8±1.6) 33.4% *	0.4±2.0 (3.7±1.16) -89.5% $^{\#}$	5.5±1.8 (4.4±1.8) 24.6% *
	T13	(control) Δ [%]	-2.0±0.7 (-1.9±0.8) 2.6%	-2.1±1.0 (-1.9±0.7) 7.8%	-2.0±1.0 (-2.0±0.7) -1.3%	-1.7±0.7 (-2.0±0.8) -16.3%	-1.8±1.2 (-1.9±1.0) -5.3%
	T17	(control) Δ [%]	-2.2±0.6 (-2.9±0.6) -24.3% $^{\#}$	-2.5±0.4 (-2.9±0.7) -12.2% *	-3.1±0.7 (-2.9±0.6) 6.5%	-1.6±0.5 (-2.9±0.6) -44.9% $^{\#}$	-3.2±0.8 (-3.0±0.8) 7.5%
	L1	(control) Δ [%]	-1.7±0.8 (-2.6±0.6) -34.7 % $^{\#}$	-2.1±0.6 (-2.5±0.8) -17.8% *	-2.9±1.0 (-2.6±0.7) 10.3%	-1.2±0.7 (-2.6±0.8) -52.5% $^{\#}$	-3.0±0.9 (-2.7±1.0) 11.9%
	L3	(control) Δ [%]	-1.5±0.9 (-2.3±0.9) -37.2% $^{\#}$	-1.8±0.9 (-2.3±1.0) -21.0% *	-2.6±0.9 (-2.3±1.0) 11.2%	-1.0±0.9 (-2.3±1.0) -58.1% $^{\#}$	-2.8±1.0 (-2.5±1.1) 11.9%
	L5	(control) Δ [%]	-0.2±1.0 (-0.4±0.7) -37.9%	-0.4±0.9 (-0.3±0.8) 4.8%	-1.0±0.9 (-0.4±0.8) 162.2% *	-0.1±1.3 (-0.5±0.8) -80.5%	-0.8±0.8 (-0.7±0.7) 24.5%

Significant differences between the positions and the control trials (HNP1) * $p<0.05$, $^{\&}p<0.01$, $^{\#}p<0.001$.

Table 2.2. Range of motion (ROM) values (mean±SD) in degrees at trot at different positions of the head and neck (HNP).

Trot			HNP2	HNP3	HNP4	HNP5	HNP6
Flexion-Extension	T10		4.6±1.5	4.9±1.9	5.8±1.7	4.4±1.6	5.6±1.6
		(control)	(5.0±1.3)	(5.0±1.4)	(5.2±1.6)	(5.5±1.6)	(4.9±1.3)
		Δ [%]	-8.7%	-2.8%	11.4% *	-20% $^{\#}$	14.4 $^{\&}$
	T13		4.6±1.4	4.7±1.5	5.3±1.5	4.6±1.2	5.4±1.6
		(control)	(4.9±1.5)	(4.9±1.5)	(5.1±1.5)	(5.2±1.4)	(4.8±1.4)
		Δ [%]	-6.3%	-4.6%	3.9%	-11.4% *	12.7% *
	T17		3.3±1.1	3.5±1.2	4.0±1.1	3.3±1.1	4.2±1.3
		(control)	(3.9±1.1)	(3.9±1.1)	(3.9±1.1)	(3.9±1.1)	(3.8±1.3)
		Δ [%]	-13.4% $^{\&}$	-10.4% *	1.7%	-15.1% $^{\#}$	8.9%
	L1		2.9±0.6	3.0±0.7	3.5±0.7	2.8±0.8	3.6±0.9
		(control)	(3.3±0.8)	(3.2±0.8)	(3.1±0.9)	(3.1±0.8)	(3.3±0.9)
		Δ [%]	-12.4% $^{\&}$	-7.6%	13.9% $^{\&}$	-10.2%	7.3%
	L3		3.7±0.5	3.8±0.7	4.1±0.5	3.5±0.5	3.8±0.6
		(control)	(3.6±0.7)	(3.5±0.7)	(3.3±0.5)	(3.2±0.5)	(3.7±0.8)
		Δ [%]	2.1%	6.7%	24.3% $^{\&}$	9.5%	4.3%
	L5		3.2±0.4	3.2±0.4	3.5±0.3	3.0±0.5	3.3±0.5
		(control)	(3.0±0.6)	(3.0±0.6)	(2.8±0.5)	(2.7±0.5)	(3.1±0.7)
		Δ [%]	8.4%	9.9%	25.4% $^{\#}$	10.1%	9.6%
Lateral bending	T10		7.6±1.5	7.2±1.9	7.7±1.7	7.4±1.6	8.6±1.6
		(control)	(8.4±1.3)	(8.3±1.4)	(8.2±1.6)	(8.1±1.6)	(8.4±1.3)
		Δ [%]	-6.0%	-13.1%	-5.3%	-9.2%	2.3%
	T13		5.2±1.1	5.1±1.4	5.6±1.3	5.3±1.1	5.7±1.3
		(control)	(5.6±1.3)	(5.5±1.3)	(5.4±1.2)	(5.4±1.2)	(5.6±1.2)
		Δ [%]	-7.8%	-8.0%	3.5%	-1.8%	2.2%
	T17		4.1±1.5	4.2±1.2	4.4±1.6	4.2±1.6	4.3±1.6
		(control)	(4.5±1.4)	(4.3±1.4)	(4.2±1.5)	(4.1±1.4)	(4.4±1.4)
		Δ [%]	-6.8%	-3.8%	5.7%	2.2%	-1.7%
	L1		3.4±0.9	3.6±0.8	3.7±0.9	3.7±1.1	3.4±0.9
		(control)	(3.6±0.9)	(3.4±0.9)	(3.3±0.8)	(3.3±0.8)	(3.5±0.8)
		Δ [%]	-5.0%	4.4%	12.1%	12.2%	-3.1%
	L3		4.5±1.1	4.7±1.5	4.7±1.3	4.8±1.3	4.7±0.9
		(control)	(4.5±1.2)	(4.5±1.1)	(4.3±1.0)	(4.3±0.7)	(4.6±1.1)
		Δ [%]	0.3%	5.5%	10.6%	11.4%	1.5%
	L5		5.8±1.5	5.8±1.5	5.9±1.4	5.9±1.6	6.3±1.4
		(control)	(6.1±1.3)	(6.1±1.3)	(5.9±1.3)	(5.8±1.2)	(6.3±1.4)
		Δ [%]	-6.0%	-4.7%	-0.3%	1.1%	0.2%
Pelvic axial rotation	S3		7.0±2.3	7.0±2.0	6.6±1.9	8.0±2.3	6.9±2.1
		(control)	(7.3±2.0)	(7.2±2.0)	(7.0±1.9)	(7.0±1.9)	(7.3±2.0)
		Δ [%]	-3.5%	-2.9%	-6.2%	13.4% $^{\&}$	-4.6%
Protraction retraction	HL		34.0±3.1	34.2±2.6	33.6±2.6	33.0±3.3	34.8±2.3
		(control)	(34.2±3.2)	(34.1±3.3)	(33.8±2.4)	(33.4±2.3)	(34.6±3.4)
		Δ [%]	-0.4%	0.2%	-0.5%	-1.4%	0.7%

Significant differences between the positions and the control trials (HNP1) * $p<0.05$, $^{\&}$ $p<0.01$, $^{\#}$ $p<0.001$.

Table 2.3. Range of motion (ROM) values (mean±SD) in degrees at walk at different positions of the head and neck (HNP).

Walk			HNP2	HNP3	HNP4	HNP5	HNP6
Flexion-extension	T10	(control) Δ [%]	5.5±1.0 (5.9±1.2) -6.6%	6.4±1.3 (5.4±1.3) 17.4%	6.8±0.9 (5.4±1.2) 25.1%*	5.1±0.9 (5.1±1.3) -1.7%	6.7±0.8 (6.4±1.0) 4.2%
	T13	(control) Δ [%]	7.3±1.4 (7.1±1.1) 2.7%	7.4±1.4 (6.8±1.3) 10.2%	7.6±1.0 (6.8±1.1) 12.1%	6.8±1.2 (6.4±1.2) 5.7%	8.2±1.0 (7.8±1.1) 5.9%
	T17	(control) Δ [%]	7.5±1.2 (7.7±1.4) -3.0%	7.5±1.3 (7.5±1.5) 0.7%	7.5±1.1 (7.4±1.2) 1.1%	6.7±0.8 (6.9±1.3) -3.3%	9.1±1.4 (8.6±1.4) 6.4%
	L1	(control) Δ [%]	7.0±1.5 (7.6±1.4) -7.6%	7.0±1.4 (7.4±1.4) -5.3%	7.0±1.3 (7.3±1.3) -3.8%	5.9±1.1 (6.7±1.3) -11.8%	9.1±1.6 (8.6±1.6) 5.5%
	L3	(control) Δ [%]	7.2±1.4 (7.9±1.2) -9.0%	7.1±1.3 (7.6±1.2) -6.5%	7.0±1.3 (7.5±1.1) -6.8%	6.0±1.1 (7.0±1.2) -14.5% *	9.3±1.4 (8.9±1.4) 4.3%
	L5	(control) Δ [%]	5.9±1.8 (6.8±1.3) -12.5% *	5.9±1.4 (6.6±1.2) -10.8%	6.1±1.5 (6.5±1.4) -6.2%	5.0±1.7 (6.1±1.4) -17.6% $^{\&}$	8.0±1.8 (7.6±1.6) 6.4%
Lateral bending	T10	(control) Δ [%]	11.5±1.7 (11.7±1.7) -1.8%	11.2±1.4 (11.6±1.5) -3.2%	10.6±1.2 (11.2±2.1) -5.6%	11.5±1.7 (10.9±2.0) 5.5%	11.8±1.1 (11.9±1.1) -1.0%
	T13	(control) Δ [%]	6.9±1.3 (6.8±1.9) 1.3%	7.0±1.6 (6.9±2.1) 0.5%	6.3±1.3 (6.7±2.3) -6.9%	7.5±1.6 (6.5±2.2) 14.5% $^{\&}$	6.9±1.9 (6.9±1.9) -0.2%
	T17	(control) Δ [%]	4.4±1.4 (4.0±1.7) 9.7%	4.3±1.3 (4.1±1.8) 4.5%	3.9±1.5 (4.1±1.9) -5.2%	4.7±1.2 (3.9±1.8) 21.7% $^{\&}$	4.0±1.6 (4.3±1.8) -7.0%
	L1	(control) Δ [%]	4.1±1.3 (3.6±1.1) 11.6%	4.1±1.2 (3.9±1.2) 4.2%	3.7±1.2 (3.9±1.3) -6.2%	4.0±1.3 (3.8±1.4) 4.0%	4.0±1.0 (3.9±1.3) 4.1%
	L3	(control) Δ [%]	5.9±2.5 (5.6±1.9) 4.9%	5.9±2.2 (5.6±2.1) 4.6%	5.7±1.6 (5.7±2.2) -0.2%	5.6±2.5 (5.8±2.2) -2.3%	6.1±1.8 (5.8±2.5) 4.9%
	L5	(control) Δ [%]	7.3±2.4 (7.2±2.2) 2.6%	7.4±2.2 (7.1±2.5) 3.9%	7.0±1.7 (7.2±2.6) -2.8%	7.0±2.3 (7.3±2.3) -3.9%	7.7±2.3 (7.3±2.9) 4.9%
Pelvic axial rotation	S3	(control) Δ [%]	9.9±1.6 (10.8±1.4) -8.1%	10.3±2.1 (10.4±1.7) -1.5%	10.7±1.5 (10.5±1.4) 1.7%	8.4±2.2 (10.0±1.0) -15.7% $^{\#}$	11.7±1.6 (11.1±1.5) 5.7%
Protraction retraction	HL	(control) Δ [%]	38.1±4.8 (39.6±4.0) -3.8%	38.3±4.4 (38.9±4.3) -1.6%	38.5±4.2 (38.9±4.3) -1.0%	37.7±1.5 (40.1±1.4) -6.0% $^{\#}$	40.5±3.8 (40.8±3.8) -0.7%

Significant differences between the positions and the control trials (HNP1) * $p<0.05$, $^{\&}$ $p<0.01$, $^{\#}$ $p<0.001$.

Discussion

The horses used in this study had a similar and, purposefully, high level of dressage education, which ensured a comparably high quality of performance throughout the study. All of them were able to achieve successfully the required positions of the head and neck.

All the imposed head/neck positions caused thoracolumbar kinematics to differ significantly from those in the control condition, but to different extent. From the point of view of back kinematics, the more extreme positions (HNP4 and 5) induced more changes than the less extreme positions (HNP2, 3 and 6), an outcome which largely supports the hypothesis put forward in the introduction of this paper.

The angular motion patterns provided some insight in the character of the kinematic changes that were induced by the different head and neck positions. The different positions can be separated into two groups that correspond with a more elevated position of the neck and head (HNP2, 3 and 5) or a more lowered position (HNP4 and 6). In the first group the most cranial part of the thoracic spine extends more, mAMP of the intermediate part of the thoracic spine remained unchanged, and in the more caudal thoracic part and lumbar area the flexion increased. A similar, but opposite pattern was seen in HNP4 with increased flexion in the cranial thoracic region and increased extension when going more in caudal direction. Thus, there was something like a sigmoidal response of the thoracolumbar kinematics to changes in head and neck position. Upward positioning of the neck resulted in an extension of the cranial part of the thoracolumbar spine, and a flexion (or less extension) of the more caudally located part. A lowered neck position gave the opposite reaction. This pattern seems to be governed by anatomical constraints: as long as the position of the pelvis does not change with respect to ground level, an overall increase in either flexion or extension of the entire thoracolumbar spine will not be possible and any change induced in the anterior segment will have to be compensated by a change in opposite direction more caudally.

Changes in thoracolumbar kinematics were larger and occurred at different locations in the positions where either extension (HNP5) or flexion (HNP4) were more extreme than in other positions (HNP2, 3 and HNP6). Flexion-extension ROM was reduced most in the extreme high position of the head and neck (HNP5), in agreement with findings by Rhodin *et al.* (2005). It could be observed that the horses were most uncomfortable in HNP5. This apparent lack of comfort was evidenced by the fact that only in HNP5 there was a significant decrease in the intravertebral pattern symmetry compared with the free position, in which the symmetry is close to perfect. Further, horses showed an increase in lateral bending only in this position. These results were in accordance with results of Rhodin *et al*. (2005) and can probably be seen as a compensatory mechanism for the reduction of lumbar and lumbosacral flexion-extension. Also, HNP5 was the only position in which hind limb protraction was influenced. The reduction found at walk was in agreement with the mechanism that underlies the bow-and-string principle of equine back biomechanics (Slijper 1946), in which hind limb protraction was supposed to result in a tensing of the bow, i.e. flexing the back, and vice versa an extension of the back can thus be expected to result in a reduction of hind limb protraction (van Weeren 2004). Together with the protraction angle, the stride length was also reduced in this position, as will also be shown in a parallel study (Weishaupt *et al*. 2006). Changes in linear stride kinematics, earlier described by Rhodin *et al*. (2005), will influence the biomechanics of the entire horse. In HNP4 flexion-extension ROM was increased at T10 at walk, and at T10 and all lumbar vertebrae at trot, thus in most of the thoracolumbar spine. This finding lends credibility to the statement that a low position of the neck and head may be a useful aid in the gymnastic training of a horse (Janssen 2003). In the study of Rhodin *et al*. (2005), there were no significant changes in the flexion-extension ROM, which may be related to the fact that the population of horses used in that study was mixed (including both dressage horses and show jumpers) and of a lower performance level; it has been shown that the length of the lumbar back was longer in dressage horses than in show jumpers (Johnston *et al*. 2004). Back length has been shown to be positively correlated to lateral bending of the thoracic back, but can be supposed to influence flexion-extension capacity as well (Johnston *et al*. 2002).

There are some limitations when interpreting the results of this study. First, the results apply to the unridden horse and cannot be directly extrapolated to the ridden situation in which the rider has influence on the horse kinematics. However, the study gives useful information about the mechanistic reaction patterns of the horse to changes in the head and neck position that anyhow will form the basis for compensatory mechanisms when ridden. Second, while many changes were statistically significant, some were rather small. This fact allows discussion concerning the biological relevance of these findings. Currently, it is unknown what magnitude of changes in back kinematics has long-term effects over locomotion and if small changes could lead to certain injuries. This argument may apply to the positions with mild changes on the head and neck (HNP2 and 6), but much less to the more extreme positions (HNP5, 4 and to a certain extent 3). While there will be unanimity in the equestrian community that HNP5 was a faulty and undesired position, there exists large controversy about HNP4 or positions even more extremely flexed.

It can be concluded that changes in head and neck position significantly affect thoracolumbar kinematics in the unridden horse. Elevating the head/neck leads to extension in the cranial part of the spine and flexion in the caudal part and lowering the head/neck has the opposite effect. Changes are larger with more extreme positions, but extension of the neck seems to restrict the spinal range of motion more than flexion. These findings are relevant for the discussion on the ethical acceptability of certain equestrian practices.

Manufacturers' addresses

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Chapter 3

The effect of induced forelimb lameness on thoracolumbar kinematics during treadmill locomotion

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Summary

Reasons for performing the study: Lameness has often been suggested to result in altered movement of the back, but there are no detailed studies describing such a relationship in quantitative terms.

Objectives: To quantify the effect of induced subtle forelimb lameness on thoracolumbar kinematics in the horse.

Methods: Kinematics of 6 riding horses was measured at walk and at trot on a treadmill before and after the induction of reversible forelimb lameness grade 2 (AAEP scale 1-5). Ground reaction forces (GRF) for individual limbs were calculated from kinematics.

Results: The horses significantly unloaded the painful limb by 11.5% at trot, while unloading at walk was not significant. The overall flexion-extension range of back motion decreased on average by 0.2° at walk and increased by 3.3° at trot ($p<0.05$). Changes in angular motion patterns of vertebral joints were noted only at trot, with an increase in flexion of 0.9° at T10 (i.e. angle between T6, T10 and T13) during the stance phase of the sound diagonal and an increase in extension of the thoracolumbar area during stance of the lame diagonal (0.7° at T13, 0.8° at T17, 0.5° at L1, 0.4° at L3 and 0.3° at L5) ($p<0.05$). Lameness further caused a lateral bending of the cranial thoracic vertebral column towards the lame side (1.3° at T10 and 0.9° at T13) ($p<0.05$) during stance of the lame diagonal.

Conclusions: Both range of motion and vertebral angular motion patterns are affected by subtle forelimb lameness. At walk, the effect is minimal, at trot the horses increased the vertebral range of motion and changed the pattern of thoracolumbar motion 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 on the affected limb.

Potential relevance: Subtle forelimb lameness affects thoracolumbar kinematics. Future studies should aim at elucidating whether the altered movement patterns lead to back and/or neck dysfunction in the case of chronic lameness.

Keywords: Back kinematics, riding horses, induced forelimb lameness.

Introduction

The present-day equine practitioner is confronted with increasing numbers of patients presented for poor performance, subtle gait irregularities or alleged back problems. Although it is obvious that the axial skeleton is the link between the extremities, there is controversy as to the relationship between back problems and lameness. In a population of horses presented for orthopaedic problems, 26% of the patients had concurrent lameness and back pain upon palpation (Landman *et al*. 2004). Dyson (2005) reported that in the majority of horses with primary thoracolumbar or sacroiliac pain overt lameness was not a feature, but many horses showed restricted hindlimb propulsion, poor hindlimb engagement and a low-grade toe drag. These are, however, qualitative studies in patients based on clinical judgment and with dissimilar criteria. Besides, thoracolumbar abnormalities secondary to lameness have not been fully described. Experimental, quantitative lameness-studies on whole body dynamics have been conducted (Buchner *et al*. 1995, 1996a, 1996b; Keegan *et al*. 2000; Vorstenbosch *et al*. 1997), but these focused more on head and trunk movements than on specific thoracolumbar kinematics. Pourcelot *et al*. (1998) demonstrated a small influence of induced lameness on dorsoventral mobility, but relatively little detail was provided because only 4 markers were used to analyze back mobility.

Recent developments in analyzing 3-dimensional thoracolumbar kinematics based on the work by Faber *et al*. (1999, 2000) and Johnston *et al*. (2002) have created the possibility of accurately analyzing the effect of specific conditions or interventions on equine back kinematics. So far, this analysis has been used successfully to study the influence of physiological factors (Johnston *et al*. 2004), of the presence of clinical back pain (Wennerstrand *et al*. 2004), and of specific head and/or neck positions (Rhodin *et al*. 2005; Gómez Álvarez *et al*. 2006) on thoracolumbar kinematics. The present study aims at the elucidation of the effect of subtle forelimb lameness on back kinematics using the same analysis. The study was conducted as a first assessment of the relation between sub-clinical lameness and back and neck motion to improve the basic knowledge on secondary back problems. The hypothesis to be tested was that even a subtle lameness would result in a measurable change in thoracolumbar kinematics. For this purpose, we determined the kinematics of the vertebral column and the limbs in horses at walk and trot on a treadmill before and after the induction of fully reversible, subtle forelimb lameness.

Materials and Methods

Horses

Kinematics of the back was measured in six sound Dutch Warmblood horses without lameness or other abnormalities, with 11.7±4.9 years of age, a height at the withers of 163±4.8 cm, and a body mass of 577±37.1 kg, while they were walking (1.6 m/s) and trotting (4.0 m/s) on a treadmill. The horses had been trained previously and were well accustomed to the treadmill. The experimental protocol had been approved by the Animal Experimentation Committee of Utrecht University.

Lameness induction

Reversible lameness was induced in the left forelimb with a modified shoe featuring a nut welded to the inner side of the toe region. A bolt in the nut could be tightened to exert pressure on the sole, thus provoking pain. A more extensive description of the technique can be found elsewhere (Merkens and Schamhardt 1988). The lameness provoked was of grade 2 of the AAEP scale (lameness difficult to observe at a walk or trot in a straight line; consistently apparent under some circumstances, such as weight carrying, circling, inclines, hard surface) (Stashak 2002).

Quantification of lameness

The method used to quantify the lameness made use of the fact that during a supporting-limb lameness the horse tries to reduce the load of the painful limb (Buchner *et al*. 1996b). Therefore, loads on individual limbs were calculated from kinematics according to a recently developed method (Bobbert *et al*. 2007; McGuigan and Wilson 2003). The method involves the calculation of the total ground reaction force (GRF) from kinematics (Bobbert and Santamaría 2005), followed by the determination of the distribution of this force over individual limbs in those phases of the stride cycle where only two limbs are in contact with the ground. It has been shown that changes in peak individual limb reaction forces over time can be calculated using this method with a standard error of measurement of 0.2 N/kg. At walk, the GRF were calculated from the distal limb length assuming that the distal limbs operate as linear springs, of which the force-length relationships were determined using calculated individual limb forces at trot (Bobbert *et al*. 2007).

Data collection

Measurements were performed using the infrared-based ProReflex® automated gait analysis system[1], operating at 100 Hz. Spherical infrared light reflective markers with a diameter of 19 mm were glued to the skin over the spinous processes of thoracic vertebrae 6, 10, 13 and 17 (T6, T10, T13, T17), the lumbar vertebrae 1, 3 and 5 (L1, L3, L5), and the 3rd sacral vertebra (S3). Markers were also placed on the coxal tuberosities, and to the lateral sides of the hooves. Also, markers were located on the limbs, head and neck (Bobbert and Santamaría 2005). Six infrared cameras situated at both sides of the treadmill recorded the marker locations while the horses were standing square and at walk and trot before, during and after the induced lameness. The actual recordings were performed during 10 seconds after 1 minute of locomotion on the treadmill. The treadmill was stopped for 1 minute between the three consecutive measurement sessions (before, during and after induction of the lameness) in order to tighten the bolt in the shoe or to remove it.

Data analysis

Qualisys Track Manager Software[1] was used to capture and process the data. A standard right-handed orthogonal Cartesian coordinate system was used to describe the motion of the vertebral column. Motion was described as flexion-extension (in the sagittal plane), lateral bending (in the horizontal plane), and axial rotation of the pelvis (in the transversal plane). All the vertebral movements were calculated using Backkin®[1] and presented as angular motion patterns (AMP) during the stride cycle. The range of motion (ROM) was calculated for each AMP and was defined as the difference between maximal and minimal values of the AMP. Data captured in the square standing horse before and after the lameness induction were used to determine the zero value in the AMPs in each horse. The vertebral angles were defined as the angle between three adjacent marked vertebrae (e.g., the angle at T10 is the angle between the line from T6 to T10 and the line from T10 to T13). The calculated angles are shown in Figure 3.1. The overall flexion-extension range of motion was the average of the ranges of motion of all the vertebral angles in the sagittal plane. The beginning of each stride cycle was taken to be the initial ground contact of the left hindlimb. The correlation coefficient between the vertebral angular motion patterns was calculated to quantify the intra-vertebral pattern symmetry (Faber *et al*. 2000). The neck angle was calculated as the angle between the markers on T6 and atlas and the horizontal plane. Stride length was calculated from the marker on the left hindlimb. Protraction-retraction angle was calculated for the four limbs using the markers on the hooves and T6 for the forelimbs, and the hooves and S3 for the hindlimbs.

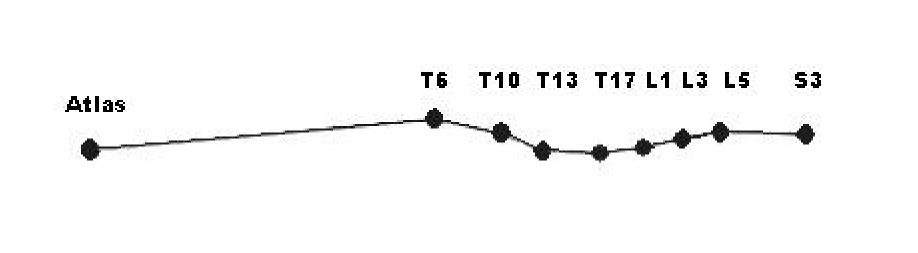

Figure 3.1. Markers and the calculated angles of the back and neck in the sagittal plane.

The distribution of values for kinematic variables and calculated forces was tested for normality. If normally distributed, further analysis was carried out using ANOVA for repeated measures and a Bonferroni correction. The overall range of motion was analyzed for variance deviations, with the different vertebrae of individual animals being treated as repeated-measures. If data were not normally distributed a Wilcoxon signed rank test was used. The level of significance was set at $p<0.05$.

Results

Quantification of lameness

The lame limb was significantly unloaded only at trot. The peak vertical ground reaction force on the lame limb significantly decreased from 13.1±1.5 N/kg to 11.6±1.4 N/kg ($p<0.05$). At walk, the peak vertical GRF on the lame limb was 7.3±1.0 N/kg before the lameness induction and 7.1±0.9 N/kg during lameness.

Stride length and protraction-retraction angle

There were no significant changes in the stride length or in the protraction-retraction angle of the 4 limbs in either of the gaits (Table 3.1).

Vertebral Range of motion

At walk, the overall flexion-extension ROM of the vertebral column was significantly reduced from 6.2 to 6.0 degrees in the lame condition (Fig. 3.2a). However, when testing the range of motion of the individual vertebral angles, the range of motion in the lame condition was significantly smaller only at T10, L1 and L5. In the lame condition there was a significant increase in lateral bending range of motion at L5 only and no change in axial rotation of the pelvis (Table 3.1).

Table 3.1. Range of motion (ROM) values (mean ± SD, degrees), neck angles (degrees), stride length (meters) and protraction-retraction angles (degrees) at walk and trot in horses with induced subtle forelimb lameness.

Motion		Walk		Trot	
		sound	lame	sound	Lame
Flexion-extension	T10	5.1±1.0*	4.8±0.9*	3.4±0.6*	4.0±0.8*
	T13	6.3±0.6	6.1±0.9	2.3±0.7 *	2.9±0.6 *
	T17	6.8±1.0	6.6±1.4	2.3±0.4	2.6±0.4
	L1	6.6±1.4*	6.4±1.7*	2.8±1.0	2.9±0.7
	L3	6.4±2.0	6.1±2.0	2.9±0.7	3.0±0.7
	L5	5.9±2.0*	5.7±2.1*	2.9±0.7	2.9±0.9
	Overall variation	6.2±1.3*	6.0±1.5*	2.8±0.7*	3.1±0.7*
Lateral bending	T10	8.9±1.9	8.9±2.0	7.2±1.2 *	6.7±1.6 *
	T13	5.0±1.0	4.6±1.2	4.3±1.3	4.1±1.3
	T17	3.2±0.9	3.1±1.0	3.3±0.9	3.4±0.9
	L1	4.0±1.4	4.4±0.7	3.1±0.9	3.1±0.8
	L3	5.3±1.6	6.0±1.6	3.9±1.1	3.9±0.9
	L5	6.7±1.9*	7.3±1.7*	4.7±0.9	4.6±0.9
Pelvic axial rotation	S3	9.6±1.3	9.4±1.7	6.2±0.7 *	5.6±0.9 *
Neck angle		94.4±2.6	90.6±2.4	103.1±1.0*	95±1.3*
Stride length		1.8±0.2	1.9±0.1	2.8±0.1	2.8±0.1
Protraction-retraction angles	Hind right limb max protraction max retraction ROM	 14.33 -26.17 40.50	 14.38 -25.73 40.11	 12.45 -25.98 38.43	 12.01 -27.54 39.55
	Hind left limb max protraction max retraction ROM	 15.59 -23.90 39.49	 13.93 -26.40 40.34	 11.41 -26.71 38.12	 12.25 -25.28 37.53
	Fore right limb max protraction max retraction ROM	 16.66 -23.10 39.76	 16.33 -22.69 39.02	 16.85 -23.59 40.44	 17.52 -23.90 41.42
	Fore left limb max protraction max retraction ROM	 16.77 -22.47 39.25	 17.03 -22.79 39.82	 17.81 -24.87 42.69	 18.43 -23.81 42.24

* Statistically significant differences between sound and lame condition.

At trot, the overall vertebral flexion-extension ROM increased significantly from 2.8 to 3.1 degrees during lameness (Fig. 3.2b). This increase was individually significant at T10 and T13. Besides, there was a significant decrease in the lateral bending range of motion at T10 and in the axial rotation range of motion of the pelvis (Table 3.1).

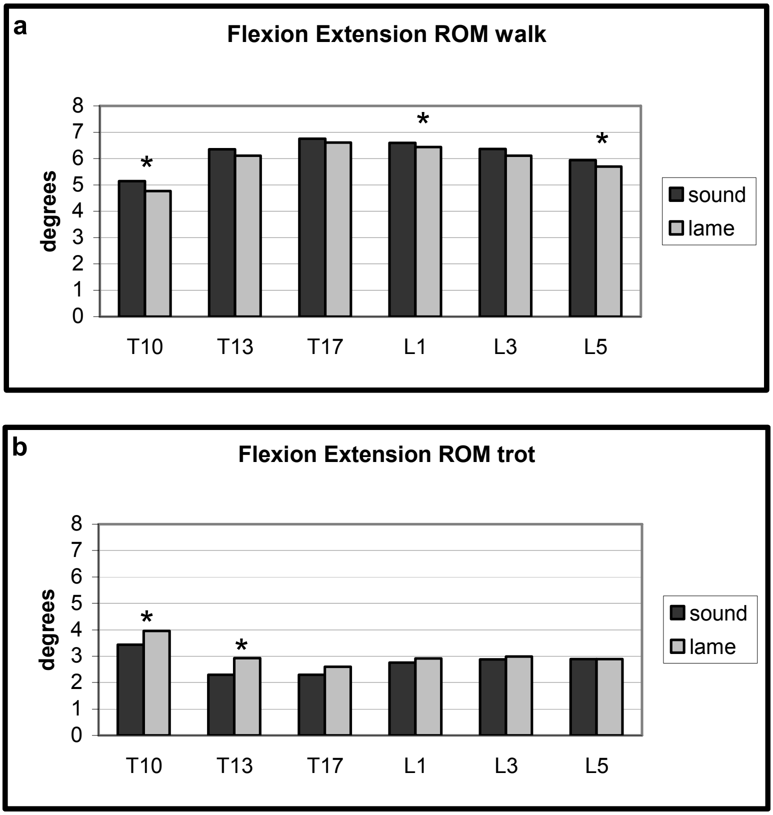

Figure 3.2. Flexion-extension range of motion (ROM) values (means in degrees) of every vertebral angle at walk (a) and trot (b) in horses before (sound) and during (lame) subtle forelimb lameness induction. * Statistically significant differences between sound and lame condition.

Vertebral Angular motion patterns

Changes in the patterns of the vertebral angles were observed at trot. There was a significant increase of 0.9 degrees in flexion at T10 during the stance phase of the sound diagonal. During the entire stance phase of the lame diagonal there was a significantly increased extension of 0.7 degrees at T13 and 0.8 degrees at T17, whereas increased extension of 0.5 degrees at L1, 0.4 degrees at L3 and 0.3 degrees at L5 were only seen at mid-stance, i.e. when the loading of the lame limb is maximal (Fig. 3.3).

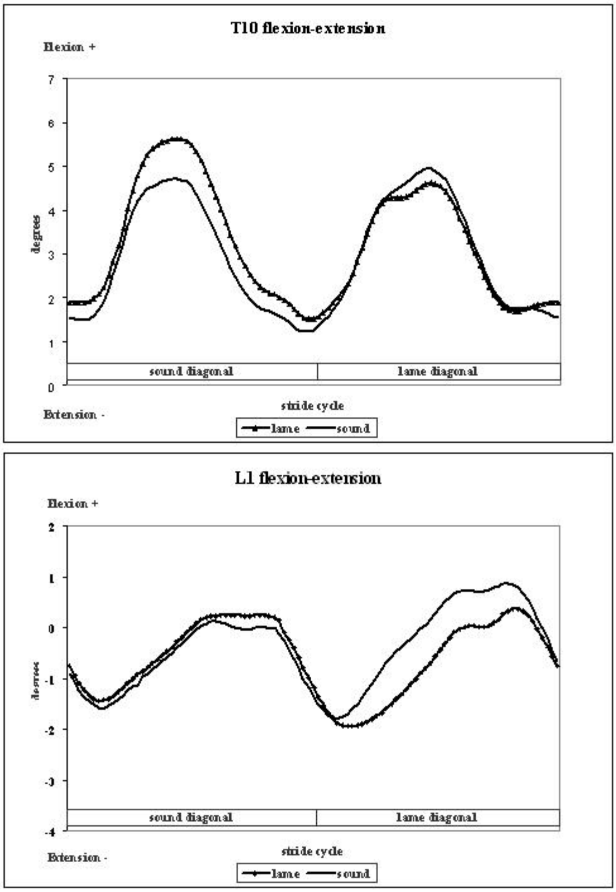

Figure 3.3. Flexion-extension angular motion pattern (AMP) at T10 and L1 from a horse at trot before (sound) and during (lame) induction of subtle forelimb lameness. Values in square standing position have been used to determine the zero reference value in the AMPs.

There was a significant increase in bending towards the left (which was the lame side) of 1.3 degrees at T10 and of 0.9 degrees at T13 at mid-stance of the lame diagonal. There were no changes in lateral bending in the lumbar region or in the axial rotation of the pelvis.

Intra-vertebral pattern symmetry

There was a significant decrease in the symmetry of the lateral bending intra-vertebral pattern at trot during lameness, which was 96% at T10 and 95% at T13, compared with 97% of symmetry in the control measurements for both vertebral angles.

Neck angle

The neck had, on average over the entire stride cycle, a lower position at trot. This is indicated by a reduction of 7.9% in the neck angle (Table 3.1).

Discussion

The results of this study support the hypothesis that subtle lameness results in a measurable change in thoracolumbar kinematics. It was a deliberate choice to induce a very subtle lameness. A severe lameness would have disrupted the entire chain of motion of the various body segments and would therefore inevitably have affected back motion as well. Theoretically, a subtle lameness could be absorbed in the proximal parts of the limbs and would then not be transmitted to the trunk and the axial skeleton. A subtle lameness is, by definition, difficult to perceive and grade by the human eye. For this reason a quantitative approach was chosen to define the lameness, based on the fact that a horse with a supporting lameness will always to some extent try to remove load from the affected limb (Buchner *et al*. 1996b). Consequently, knowing the loading of the individual limbs, it is possible to prove or disprove the existence of a supporting lameness. In this study an objective method, based on the calculations of the ground reaction forces from kinematic data (Bobbert *et al*. 2007; McGuigan and Wilson 2003) were used. Through this approach it was indeed possible to demonstrate the existence of a subtle lameness at trot, shown by a reduction of the peak forelimb vertical GRF by 11.5%. Such a reduction was also observed by Weishaupt *et al*. (2006), who measured horses featuring a subtle forelimb lameness directly with an instrumented treadmill. In that study the peak forelimb vertical GRF decreased with only 4%, but speed was lower (3.5 m/s). In our study the subtle lameness did not have a significant influence on the linear and temporal stride variables, which is in agreement with earlier studies on induced lameness (Buchner *et al*. 1995; Weishaupt *et al*. 2006).

The flexion-extension range of motion of the whole thoracolumbar vertebral column was significantly increased at trot in the lame condition. This increase was most evident in the cranial thoracic area. It is known that an increased vertical range of motion of the head is an indicator of forelimb lameness (Keegan *et al*. 2000). By modification of the motion pattern of the head, the horse reduces the load on the painful limb (Buchner *et al*. 1996a; Keegan *et al*. 2000; Vorstenbosch *et al*. 1997). Given the connection of the head to the thoracolumbar vertebral column through the neck, the increased range of motion of the cranial thoracic vertebral column does not come as a surprise. At walk, the overall range of motion was reduced rather than increased. This difference in sign between the adaptation at walk and the adaptation at trot may be explained by the fact that a subtle lameness provokes evident changes in head motion patterns only at trot and not at walk due to the much larger ground reaction forces at trot, implying that there is no need for compensatory movements of the head, neck and back at walk. The slight reduction in flexion-extension range of motion at walk may reflect an overall increase in stiffness of the back as a response to very mild pain sensed by the horse, which may affect in this way the relatively high-amplitude free-swinging motion of the back that is characteristic of the walk in the completely sound horse. Such a reduction of the flexion-extension of the vertebral column possibly could lead to chronic stiffness of the back, chronic back pain and/or persistent rigidity.

At trot, the increased flexion at T10 in the lame condition during the stance phase of the sound diagonal is in line with the lowering of the neck (and head) during the stance phase of the sound limb (Vorstenbosch *et al*. 1997). As a consequence of the low position of the neck (and head), an increased flexion of the thoracic part of the trunk will be induced (Gómez Álvarez *et al*. 2006). Furthermore, during the lame diagonal stance phase the rest of the back (T13, T17, L1, L3 and L5) was more extended while the cranial thoracic area (T10 and T13) was bending laterally towards the lame side. As a compensatory mechanism in lameness, the vertical force of the lame limb shifts to the hindlimbs in the lame diagonal and to the sound forelimb during the sound diagonal (Weishaupt *et al*. 2006). In addition, an upward movement and a lower peak vertical acceleration of the head help to unload the limb in the vertical plane during the lame stance phase (Buchner *et al*. 1996a). These compensatory mechanisms can thus be supposed to induce extension of the vertebral column and a shift of the centre of gravity towards the sound side and towards the hind quarters in the horizontal plane (Buchner *et al*. 2001; Marks 1999). A shift away from the lame side in the horizontal plane can only be carried out through a lateral bending of the vertebral column with the concave side at the lame side and the convex side at the sound side, i.e. a bending towards the lame side. Such an action could be modulated through a contraction of the *longissimus lumborum* muscle; EMG studies of this muscle have shown that it may act to limit the lateral bending of the trunk (Tokuriki *et al*. 1997). The *longissimus dorsi* muscle may play a role too, as it is mainly responsible for stabilization of the vertebral column in a response to dynamic forces (Licka *et al*. 2004).

Some changes in angular motion patterns at individual vertebrae were not statistically significant in this study, but these findings were consistently observed in consecutive vertebral segments. When taken as a whole, there was a significant change in thoracolumbar motion in those cases. It should be emphasised that the changes were provoked by an intentionally very slight lameness that was hardly perceptible to the eye, and that only acute effects were measured. If a horse suffers from a chronic ailment of the limb, as will almost invariably be the case in clinical cases, long-term adaptation processes might ultimately lead to chronic back problems, recurrent acute episodes of soreness, or just permanent minor spinal muscle pain due to asymmetrical loading of the spine. Such conditions might affect the performance of horses and might also provoke biomechanical compensations, which could lead to pathologies in other areas.

It is concluded that subtle forelimb lameness affects both the range of motion and the vertebral angular motion patterns to a limited, but statistically significant extent. Not surprisingly, the effect is best detectable in the cranial thoracic region. When the sound diagonal is loaded, horses tend to flex the cranial thoracic back, which follows the movement of the neck and head downwards. When the lame diagonal is loaded, they extend the rest of the back, shifting the mass to the hind quarters away from the painful limb. They will further increase lateral bending towards the lame diagonal when it is loaded, bringing the centre of gravity more towards the sound side. The changes are relatively minor in extent, but might affect muscular tension and vertebral function when present for a prolonged period of time in cases of chronic lameness. The observations therefore lend credibility to the alleged implication of subclinical lameness in the pathogenesis of vertebral dysfunction in horses. However, further research is necessary to demonstrate this relationship unequivocally and to understand the long-term adaptation processes.

Manufacturers' addresses

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Chapter 4

The effect of induced hindlimb lameness on thoracolumbar kinematics during treadmill locomotion

Under revision

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Summary

Reasons for performing the study: Hindlimb lameness has often been suggested to cause altered motion of the back, but there are no detailed studies describing such a relationship.

Objectives: To quantify the effect of induced subtle hindlimb lameness on thoracolumbar kinematics in the horse.

Methods: Kinematics of 6 riding horses was measured during walk and trot on a treadmill before, during and after the application of pressure on the sole of the left hindlimb using a well-established sole presure model. Reflective markers were located at anatomical landmarks on the limbs, back, head and neck for kinematic recordings. Ground reaction forces (GRF) in individual limbs were calculated from kinematics to detect changes in loading of the limbs.

Results: When pressure on the sole of the hindlimb was present, the horses were judged as lame (grade 2 on the AAEP scale 1-5) by an experienced clinician. No significant unloading of this limb was found in the group of horses (unloading was observed in 4 and it was not detectable in the other 2), but statistically significant effects on back kinematics were detected. The overall flexion-extension (FE) range of motion (ROM) of the vertebral column was increased at walk, especially in the thoracic segments. Axial rotation (AR) ROM of the pelvis was also increased. At trot, the FE ROM was decreased only in the segment L3-L5-S3. During the stance phase of the lame limb, the segment T6-T10-T13 was more flexed and the neck was lowered at both gaits; the thoracolumbar segments were more extended at walk and trot. There were no significant changes in the stride length or protraction-retraction angles in any of the limbs.

Conclusions: Subtle hindlimb lameness provoked slight but detectable changes in thoracolumbar kinematics. The subtle lameness induced in this study resulted in hyperextension and increased ROM of the thoracolumbar back, but also in decreased ROM of the lumbosacral segment and rotational motion changes of the pelvis.

Potential relevance: Even subtle lameness can result in changes in back kinematics, which emphasises the intricate link between limb function and thoracolumbar motion. It may be surmised that, when chronically present, subtle lameness induces back dysfunction.

Keywords: Back kinematics, riding horses, induced hindlimb lameness.

Introduction

Horses modify their gait mechanics to compensate for any injury or source of pain. Lameness is one of the most common symptoms of a locomotor disorder affecting mechanics of the entire body. Horses try to cope with lameness by several mechanisms all aiming to unload the painful limb. Compensatory mechanisms in limb loading have been described by Weishaupt *et al*. (2004), who showed a reduction of the total vertical impulse per stride, a reduction of the impulse in the lame diagonal stance phase, shifting of the impulse within the lame diagonal to the forelimb and in the sound diagonal to the hindlimb, and a decrease of the loading rate by the increase of the stance duration. In order to allow for these changes in limb loading, the motion of other parts of the body need to be changed, and these changes can to a certain extent become detectable during clinical examinations. Kinematical studies have shown that in hindlimb lameness at trot the croup is elevated at first contact of the lame limb, and is lowered during weight-bearing to descend further during the stance phase of the sound limb (Buchner *et al*. 1996a; Cadiot and Almy 1924). The head and neck are lowered during the stance phase of the lame hindlimb (Cadiot and Almy 1924; Denoix and Audigie 2001; Uhlir *et al*. 1997), and this motion pattern changes from the normal biphasic sinusoidal pattern to a curve with only a single elevation at the beginning of the sound diagonal (Denoix and Audigie 2001), likewise the trunk pattern (Buchner *et al*. 1996a). Adaptations in head and trunk movements occur in both forelimb and hindlimb lameness (Buchner *et al*. 1996a; Uhlir *et al*. 1997), together with changes in the angular motion patterns of the limbs and spatial and temporal stride parameters (Buchner *et al*. 1995; 1996b).

Given the central position of the thoracolumbar spine in the body, lameness will forcibly often affect the motion pattern of the vertebral spine, which may be manifested as a reduction in the horse's performance. Although there is no doubt that a close relationship exists between back problems and lameness, there is great need in equine practice to improve the understanding of this relationship. Landman *et al*. (2004) reported that the prevalence of lameness in horses with back problems was 74%, while the prevalence of back problems in horses with lameness was 32%. Data on lameness-induced changes in thoracolumbar motion are scarce. Pourcelot *et al*. (1998) reported in a descriptive study in a single horse that the thoracolumbar back showed less extension during the lame diagonal stance phase, but increased extension during the sound diagonal stance phase at trot. There were no data on the walk in that study.

Clinically, moderately lame horses demonstrate altered movement of the back, head and neck. In the case of hindlimb lameness we would further expect an increase in axial rotation of the pelvis, following ascending and descending motion of the croup. The effect of a very subtle lameness on spinal kinematics is more difficult to predict. With a low-grade subtle lameness the changes in back movement, if present, are presumably much smaller and most probably difficult to detect with the naked eye. Nevertheless, even small changes in back motion, when chronically present, could result in an injury or vertebral disorder. Therefore, detailed studies are necessary to fully understand the effects on back kinematics of both forelimb and hindlimb lameness. In a previous study, we showed that subtle forelimb lameness provokes changes in the thoracolumbar motion pattern and increases the range of motion in the vertical and horizontal planes at trot (Gómez Álvarez *et al*. 2007a). It is conceivable that hindlimb lameness will have a similarly effect on back motion too. However, the character of any effects might be different, given the anatomical differences between fore and hindlimbs, in particular with respect to their anatomical connection to the body.

The aim of this study was to investigate the effect of artificially induced subtle hindlimb lameness on back motion. Quantification of this effect may improve our understanding of back problems secondary to lameness. Our hypothesis was that even a subtle lameness would result in a measurable change in thoracolumbar kinematics. To test this hypothesis, we analysed the kinematics of 6 riding horses walking and trotting on a treadmill before and during the induction of reversible subtle hindlimb lameness.

Materials and Methods

Horses and general experimental design

Back and limbs kinematics were measured in six sound Dutch Warmblood horses, 11.7 ± 4.9 years of age, with a height at the withers of 163 ± 4.8 cm, and a body mass of 577 ± 37.1 kg, while walking (1.6 m/s) and trotting (4.0 m/s) on a treadmill before, during and after the induction of lameness. The horses had been trained previously on the treadmill in order to get them accustomed to treadmill locomotion. The Experimental Animals Commission of Utrecht University had approved the experimental protocol.

Lameness induction

Reversible lameness was induced in the left hindlimb with a modified shoe featuring a nut welded to the inner side of the toe region. A bolt in the nut could be tightened to exert pressure on the sole, thus provoking transient pain. A more extensive description of the technique can be found elsewhere (Merkens and Schamhardt 1988). The lameness provoked was grade 2 on the AAEP scale (lameness difficult to observe at a walk or trot in a straight line; consistently apparent under some circumstances, such as weight carrying, circling, inclines, hard surface (Stashak 2002)).

Evaluation of lameness

During a supporting limb lameness the horse tries to reduce the load of the painful limb (Buchner *et al*. 1996b). Loads of individual limbs were calculated from kinematics as proposed elsewhere (Bobbert *et al*. 2007; McGuigan and Wilson 2003). Briefly, distal limb length of the forelimb was measured using markers on the hoof and elbow joint, and of the hindlimb using markers on the hoof and stifle joint. The method involves the calculation of the total ground reaction force (GRF) from kinematics (Bobbert and Santamaria 2005), followed by the determination of the distribution of this force over individual limbs in those phases of the stride cycle where only two limbs are in contact with the ground. It has been shown that changes in peak individual limb reaction forces over time can be calculated using this method with a standard error of measurement of 0.2 N/kg. The GRFs were calculated at walk from distal limb length assuming that the distal limbs operate as linear springs. The force-length relationships that emerged from these calculations were used to calculate individual limb GRF at trot (Bobbert *et al*. 2007).

Data collection

Measurements were performed using the infrared-based ProReflex® automated gait analysis system1, operating at 100 Hz. Spherical infrared light reflective 19 mm diameter markers were glued to the skin over the spinous processes of thoracic vertebrae 6, 10, 13 and 17 (T6, T10, T13, T17), the lumbar vertebrae 1, 3 and 5 (L1, L3, L5), and the 3rd sacral vertebra (S3). Extra markers were placed on the coxal tuberosities, the lateral sides of the hooves; on the limbs for load calculations (Bobbert and Santamaria 2005), and on the atlas for the neck angle calculation. Six infrared cameras situated on both sides of the treadmill recorded the horses while standing square and while walking and trotting on the treadmill before, during and after lameness induction. The recordings were performed during 10 seconds after the first minute of locomotion on the treadmill. After capturing data in the non-lame reference condition the treadmill was stopped for 1 minute to allow for tightening of the bolt, inducing lameness, and again after the lame condition to allow for removal of the bolt.

Data analysis

Qualisys Track Manager Software[1] was used to capture and process the data and Matlab®[2] for further analyses. A standard right-handed orthogonal Cartesian coordinate system was used to describe the motion of the vertebral column. Angular motion patterns (AMP) were described as flexion-extension (in the sagittal plane), lateral bending (in the medio-lateral plane), and pelvic axial rotation (S3 with respect to the position of the markers on the coxal tuberosities looked from behind of the horse). All AMP were calculated using Backkin®[1] as means and standard deviations during several averaged stride cycles. The changes in the AMP were described according to the phase of the stride cycle when these occurred. Data captured in the square standing horse before and after the lameness induction were used to determine the reference (zero) value of the AMPs in each horse. The range of motion (ROM) was determined from each AMP by taking the difference between the maximal and minimal AMP values. Each vertebral angle was defined as the angle between three adjacent marked vertebrae (e.g., the angle at T10 is the angle between the line from T10 to T6 and the line from T10 to T13). The beginning of each stride cycle was defined as the instant of initial ground contact of the left hindlimb. The correlation coefficient between the vertebral angular motion patterns was calculated to quantify the intra-vertebral pattern symmetry (Faber *et al*. 2000). The neck angle with respect to the horizontal plane was calculated using the markers on T6 and atlas. Stride length was calculated from the hoof marker on the left hindlimb. Protraction-retraction angle was calculated for each of the forelimbs using the markers on the hooves and T6, and for each of the hindlimbs using the markers on the hooves and S3.

The distribution of values for kinematic variables and calculated forces was tested for normality. If normally distributed, analysis was carried out using ANOVA for repeated measures and a Bonferroni correction. The overall range of motion was analysed for variance deviations, with the different vertebrae of individual animals being treated as repeated measures. If data were not normally distributed a Wilcoxon signed rank test was used. The level of significance for all tests was set at $p<0.05$.

Results

Evaluation of lameness

During the pain induction, each of the horses was judged to be lame by an experienced clinician. The mean peak vertical ground reaction force on the painful hindlimb was 9.3±1.3 N/kg at trot and 4.3±0.5 N/kg at walk before lameness induction, and 9.0.±0.9N/kg at trot and 4.4±0.4 N/kg at walk during lameness, which was not a statistically significant difference. Of 6 horses, 4 showed reduced peak load on the lame limb at trot and 5 at walk, 2 (walk: one) did not show changes in the measured peak load on the lame limb. These horses increased however the peak load on the non-lame hindlimb.

Stride length and protraction retraction angle

Both protraction-retraction mean angles and stride length remained unchanged at both gaits (Table 1).

Vertebral ranges of motion

At walk, the induced lameness provoked an overall increase of the flexion-extension ROM of the vertebral column from 6.2 to 6.6 degrees (mean). A significant increase was also found at individual thoracic segments: at T10, T13 and T17. Further, the axial rotation range of motion of the pelvis was increased. At trot, the overall ROM did not differ from the sound condition, only the flexion-extension ROM at L5 was decreased (Fig. 4.1a, b) (Table 1).

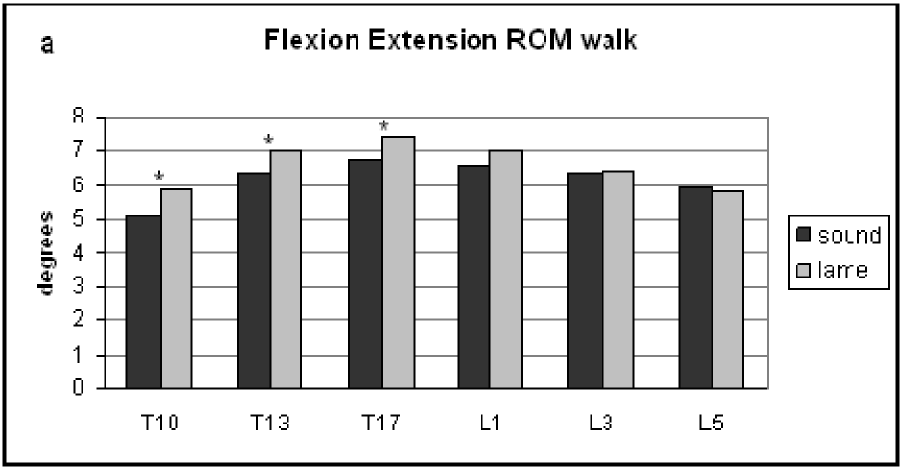
Vertebral angular motion patterns

Several changes ($p<0.05$) in the mean angular motion patterns of the vertebrae were found at walk and trot after lameness induction (Fig. 4.2). Flexion at T10 was increased by 0.8 degrees (mean of all horses) during the stance phase of the lame limb at trot and by 0.3 degrees at walk. An increase in extension was observed in the thoracolumbar area also at both gaits: at walk, there was an increase in the extension at T13 (0.5 degrees), T17 (0.7 degrees) and L1 (0.7 degrees) at the middle of the stance phase of the left (lame) hindlimb and again at the middle of the stance phase of the right (sound) hindlimb (0.8, 0.8 and 0.6 degrees, respectively), while extension at L3 and L5 was 0.6 degrees greater during the whole stance phase of the lame hindlimb (Fig. 4.2a, b). At trot, extension at T13 and T17 was increased by 0.2 and 0.3 degrees respectively, during most of the sound diagonal. No changes were observed in the lumbar segment at trot.

Table 4.1. Range of motion (ROM) values (mean ± SD, degrees) for selected individual vertebrae, neck angles (degrees), stride length (meters) and protraction-retraction angles (degrees) at walk and trot in six horses with induced subtle hindlimb lameness.

Motion		Walk		Trot	
		Sound	lame	sound	lame
Flexion-extension	T10	5.1±1.0*	5.9±1.1*	3.4±0.6	3.6±0.8
	T13	6.3±0.6*	7.0±1.1*	2.3±0.7	2.5±0.7
	T17	6.8±1.0*	7.4±1.3*	2.3±0.4	2.4±0.4
	L1	6.6±1.4	7.0±1.6	2.8±1.0	2.8±0.6
	L3	6.4±2.0	6.4±1.7	2.9±0.7	2.9±0.6
	L5	5.9±2.0	5.9±1.6	2.9±0.7*	2.6±0.8*
	Overall variation	6.2±1.3*	6.6±1.4*	2.8±0.7	2.8±0.7
Lateral bending	T10	8.9±1.9	9.3±1.6	7.2±1.2	7.5±2.2
	T13	5.0±1.0	5.3±0.9	4.3±1.3	4.3±1.2
	T17	3.2±0.9	3.3±1.2	3.3±0.9	3.3±0.9
	L1	4.0±1.4	3.9±1.5	3.1±0.9	3.2±0.8
	L3	5.3±1.6	4.9±1.6	3.9±1.1	3.8±1.1
	L5	6.7±1.9	6.4±1.3	4.7±0.9	4.5±1.1
Pelvic axial rotation	S3	9.6±1.3*	11.4±1.7*	6.2±0.7*	6.0±0.9*
Neck angle		94.4±2.6	89.9±2.3	103.1±1.0*	89.8±1.4*
Stride length		1.8±0.2	1.9±0.1	2.8±0.1	2.8±0.1
Protraction-retraction angles	Right hindlimb max protraction max retraction ROM	 14.3 -26.2 40.5	 14.5 -25.8 40.3	 12.5 -25.9 38.4	 12.5 -25.9 38.4
	Left hindlimb max protraction max retraction ROM	 15.6 -23.9 39.5	 11.2 -25.1 39.3	 11.4 -26.7 38.1	 11.8 -25.5 37.3
	Right forelimb max protraction max retraction ROM	 16.7 -23.1 39.8	 17.6 -22.4 40.0	 16.9 -23.6 40.4	 17.6 -22.9 40.5
	Left forelimb max protraction max retraction ROM	 16.8 -22.5 39.3	 16.3 -22.2 38.5	 17.8 -24.9 42.7	 19.6 -23.3 42.9

* Statistically significant differences between sound and lame condition.



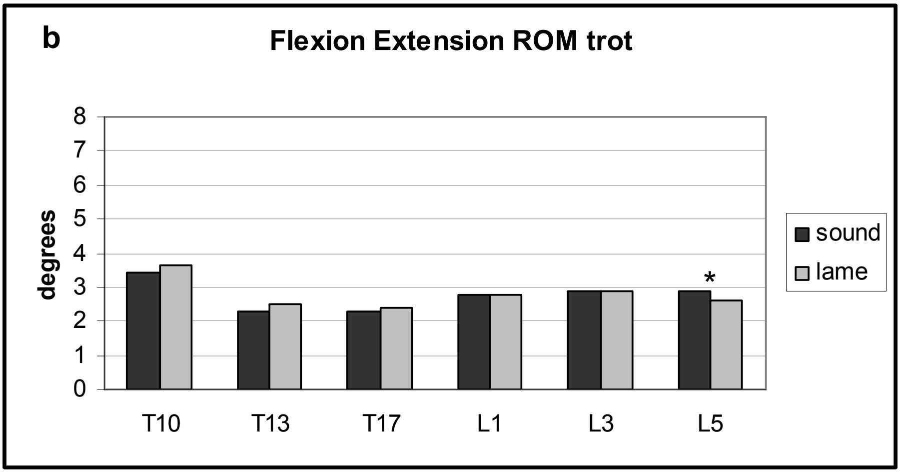


Figure 4.1. Flexion-extension range of motion (ROM) for each vertebral angle in 6 horses before (sound) and during (lame) subtle lameness caused by induced pain in the hindlimb, at a) walk and b) trot. Significant differences between sound and lame condition are indicated with *

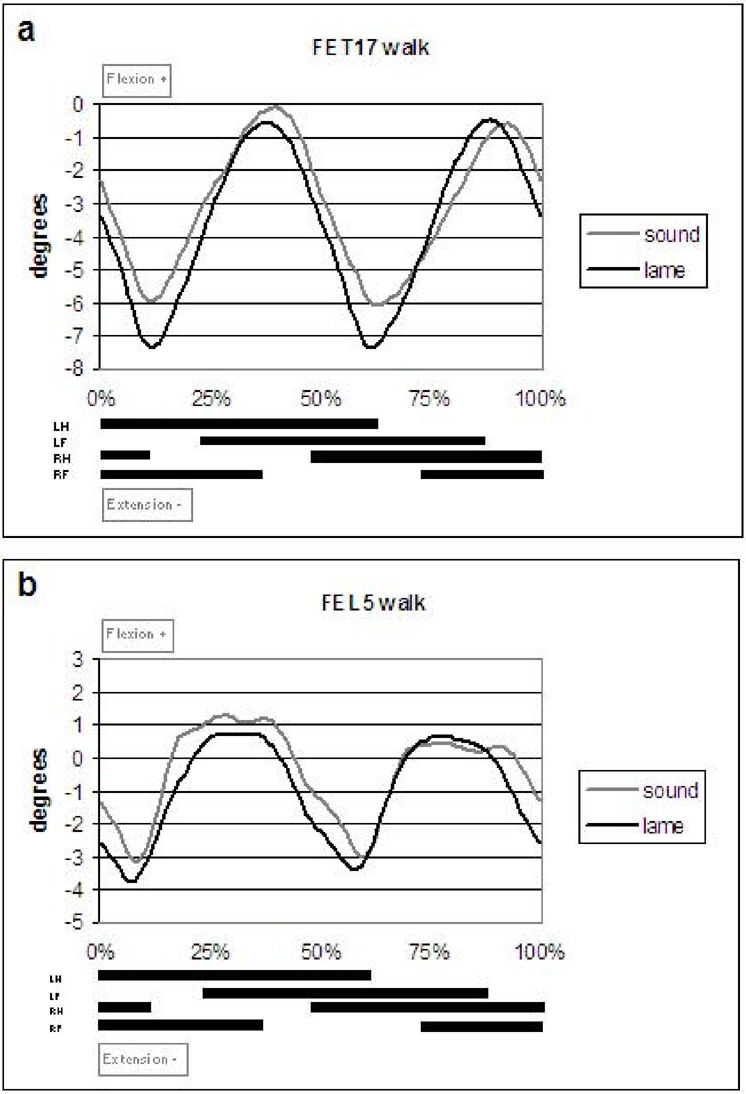


Figure 4.2. Flexion-extension angular motion patterns (AMP) of one horse at walk before (sound) and during (lame) subtle lameness caused by induced pain in the hindlimb: a) angle at T17 (T13-T17-L1) and b) angle at L5 (L3-L5-S3). The black bars at the bottom of the graph indicate the stance phases of the limbs.

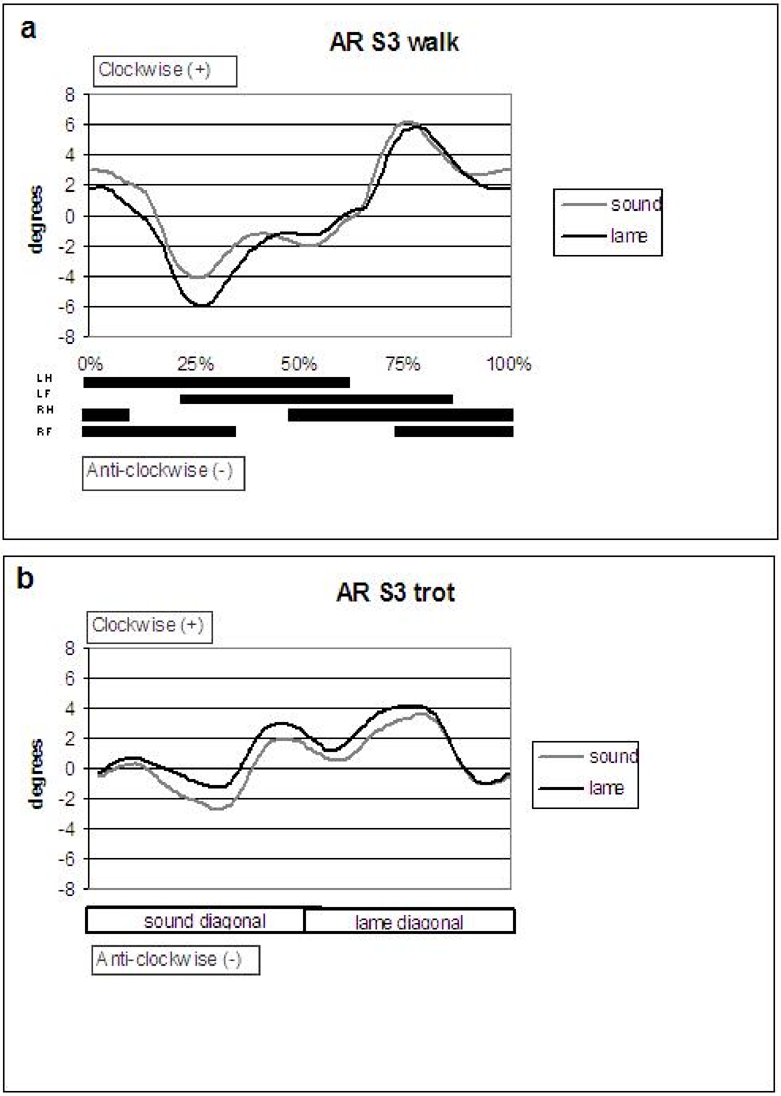


Figure 4.3. Axial rotation of the pelvis of one horse at a) walk and b) trot; before (sound) and during (lame) subtle lameness caused by induced pain in the hindlimb. Clockwise and anticlockwise directions are seen from behind of the horse. The black bars at the bottom of the graph indicate the stance phases of the limbs.

At walk, lateral bending was increased to the left (lame side) at T13 by 0.3 degrees during the end of the stance phase and the beginning of the swing phase of the lame hindlimb.

Changes in pelvic motion during walk were opposite to those during trot. During the stance phase of the lame hindlimb at walk, anticlockwise (looked from behind of the horse) rotation of the pelvis was increased by 1.2 degrees (mean); while at trot it was rotated 0.6 degrees (mean) clockwise during both diagonals (Fig. 4.3a, b).

Intravertebral pattern symmetry

The mean intravertebral pattern symmetry was unchanged by the induced lameness in most of the vertebral angles. However, it diminished at T13 for lateral bending during trot (from 97% to 94%; $P<0.05$). No changes in intravertebral pattern symmetry were observed at walk.

Neck angle

At trot, the neck was lowered during the entire stride in the lame condition. The neck angle changed on average 13.3 degrees.

Discussion

The hypothesis that subtle hindlimb lameness would result in a measurable change in thoracolumbar kinematics was supported by the outcome of this study. The induction of this subtle lameness did not result in all horses showing measurable changes in limb loading, though judged to be clinically lame. A consistent sign of lameness shown by the horses of this study was the lowering of the neck, especially at the lame diagonal at trot. This phenomenon has been described earlier (Denoix and Audigie 2001; Vorstenbosch *et al*. 1997). Stride length was not affected by the lameness, which is in agreement with other studies of induced subtle lameness (Buchner *et al*. 1995; Weishaupt *et al*. 2004). Also, protraction-retraction angle was not changed due to lameness. These somewhat inconclusive findings concur with the AAEP definition of this degree of lameness (lameness difficult to observe at a walk or trot in a straight line (Stashak 2002)), and confirm that lameness was indeed subtle. Nevertheless, detectable and systematic changes occurred in kinematics of the back at both gaits. In fact, the two horses that did not show changes in limb loading showed more apparent changes in their vertebral motion. It may be that some horses respond to a subtle lameness by changing the loading of the lame limb, while others do not change limb kinetics but instead change back kinematics and pelvic motion. The latter mechanism may affect gait relatively slightly, but does not necessarily lead to more appropriate locomotion.

Most of the changes we found in vertebral column kinematics are in agreement with the literature. Our finding of a greater averaged flexion at T10 combined with less elevation of the neck and head during the lame stance phase, is in accordance with the observation that lowering the neck helps to flex the cranial back (Gómez Álvarez *et al*. 2006). Our finding of a more extended thoracolumbar back at both gaits during the stance phase of the sound hindlimb agrees with the results of the lameness study of Pourcelot *et al*. (1998). In contrast to that study we did not find reduced extension during the lame diagonal stance phase, but this may well be due to the fact that lameness was less severe in our study, causing the associated kinematical changes to be less pronounced. The increased extension in the lumbar segment observed in the present study at walk is a new finding. Thus far, there were no reports on the effects of subtle lameness on back kinematics at walk. The increased extension may be a sign of overall stiffening of the hind quarters as a reaction to the induced pain in the sole. These changes in the motion of the lumbar segment were not seen at trot, probably because trot is an altogether different gait than walk with only two limbs on the ground simultaneously and with considerably less motion of the back (Faber *et al*. 2002) due to increased muscle activity (Robert *et al*. 2002).

The changes in range of vertical motion were different between gaits; the range increased at walk but did not change at trot. At trot, lowering the neck may to a certain extent help to avoid loading the painful limb. At walk, a similar effect may possibly be achieved by increasing the back ROM in the vertical plane. These changes occurred mainly in the thoracic area and might perhaps be interpreted as a compensatory mechanism to the tension in the lumbar area which was more extended than normal, as pointed out above. In the horse, an increased lumbar extension may go along with increased vertical ROM in the back, as has been shown earlier (Gómez Álvarez *et al*. 2006).

The changes in thoracolumbar kinematics provoked by subtle hindlimb lameness differ from those induced by forelimb lameness (Gómez Álvarez *et al*. 2007a). It is conceivable that hindlimb lameness produces more tension in the back than forelimb lameness because of the direct bony connection of back and hindlimb through the pelvis. In the fore quarters no such bony connection exists and in forelimb lameness the load on the painful limb can more easily be reduced by changing the head and neck motion, without a severe impact on thoracolumbar kinematics. The tight anatomical connection of the hindlimbs to the pelvis (and thus to the vertebral column) can explain the decrease of FE ROM at L5 at trot and the changes in the pelvic range of motion and the pattern of pelvic rotation at both gaits. At walk AR ROM of the pelvis was increased and it was rotated on average more to the lame side during the lame stance phase. At trot this AR ROM was not changed, but it was rotated to the sound side during the entire stride. Buchner *et al*. (1996a) found a reduction of the vertical displacement of the pelvis at the lame side combined with increased rotational movements. The clockwise rotation of the pelvis as found in the present study at trot is in agreement with this, as it is a rotation towards the sound side. However, vertebral reaction to lameness at walk seems to follow another mechanism and is partly effectuated through a change in lateral bending which concurs with an increase in AR of the pelvis to the same side.

In conclusion, induced subtle hindlimb lameness results in changes in thoracolumbar kinematics without necessarily producing detectable changes in the kinematics of the limbs or in ground reaction forces. Hindlimb lameness resulted in subtle back increase in extension, a slightly increased range of motion of the thoracolumbar back, a slightly decreased range of motion of the lumbosacral segment and rotational motion changes of the pelvis.

This study investigated acute effects of lameness, and long-term effects may be different. It may be presumed that also in the chronic situation compensatory changes in back kinematics will occur, which, if present for a prolonged period, might contribute to the pathogenesis of chronic back dysfunction.

Manufacturers' addresses

1 Qualisys Medical AB, Gothenburg, Sweden.
2 Matlab® (The MathWorks, Inc. Natick, Massachusetts)

Acknowledgements

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Chapter 5

Limb kinematics in horses with induced back pain

Under revision

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Summary

Reasons for performing the study: It has been shown that back pain does not affect linear and temporal stride characteristics of forelimbs or hindlimbs. It is not known, however, whether changes in limb kinematics are provoked by back pain. If present, such changes might be a cause of secondary lameness in horses with chronic back pain. Furthermore, regardless of whether they are harmless or not, they could serve as an indicator of back pain.

Objectives: To quantify the effect of induced back pain on limb kinetics and kinematics in the horse.

Methods: Limb kinematics were recorded using an infrared-based automated gait analysis system in eight Warmblood horses trotting on a treadmill at 4.0m/s. Horses were measured before, and 2 days and 7 days after, back pain was induced by injecting lactic acid into the left *longissimus dorsi* muscle. Vertical ground reaction forces on the individual limbs were calculated from kinematics.

Results: Few statistically significant changes were observed at day 2, but many at day 7. Unilateral (left sided) back pain provoked a decrease in flexion of the left and right carpal joints, right stifle and left hock joints during the swing phase (2.4, 3.2, 4.0 and 2.9 degrees, respectively). During part of the swing and part of the stance phase of the right diagonal, the distance between both fore hooves (LF and RF) and between both hind hooves (LH and RH) was increased (1.9 and 0.5 degrees, respectively). During the swing phase of the left diagonal the hind hooves were shifted to the left (painful side) relative to the 1st and 3rd lumbar vertebrae (L1 and L3), and at the same time the fore right hoof was positioned more to the right with respect to L1 ad L3 (1.2 cm RH-L1, 1.0 cm RH-L3, 1.7 cm LH-L1, 1.8 cm LH-L3, 1.6 cm RF-L1, 1.8 cm RF-L3 at day 7). There was no change in the location of the hooves relative to the rest of the vertebral markers. The pelvis showed an increased anti-clockwise axial rotation (towards the painful side) of 0.9 degrees during the stance phase of the right hindlimb at both days 2 and 7. There were no changes in the pelvic inclination, vertical ground reaction force, linear stride parameters or protraction-retraction angles.

Conclusions: The induced back pain altered the swing phase of the stride and almost did not affect the stance phase. Basically, it produced an overall decreased flexion of some of the joints during swing phase. The unilateral pain induction provoked a change in pelvic rotation and a small relative displacement of the hindlimbs to the painful side and of the right fore hoof to the opposite side with respect to the lumbar back.

Potential relevance: Although moderate back pain did not affect temporal and linear stride characteristics and may not lead to overt lameness, it provokes subtle changes in limb kinematics during swing phase which clinically can be recognized as dragging limbs and less animated gait.

Keywords: equine; horse; limbs kinematics; back pain, pain induction

Introduction

The interaction between lameness and back function has long intrigued the equine practitioner, and has been the subject of debate. The general concept of the bow and string has been put forward (Slijper, 1946), where the bow represents the back and the string represent the abdominal wall. The bow and string are influenced by the protraction and retraction of the limbs, the movement of the head, the contraction of abdominal muscles and the intrinsic back muscles (epaxial and hypaxial), and the weight of the abdominal content. The concept helps us to understand the anatomical and functional relation between the vertebral column and the limbs, but cannot be used for the detailed prediction of the mutual influences of minor changes in back and limb motion during subtle supporting limb lameness or moderate back pain.

Lameness and back dysfunction are closely related, but the exact nature of this relationship is enigmatic. Few studies in patients have been done. Landman *et al*. (2004) clinically diagnosed lameness and back pain occurring together in 26% of the horses from a population of 805 patients with orthopaedic problems. Dyson (2005) observed concurrent forelimb and hindlimb lameness in 46% of horses with thoracolumbar or sacroiliacal pain. Unfortunately, while these cross-sectional studies give an idea about the prevalence of back pain and its concurrence with lameness, they do not establish causal relationships. Investigation of causal relationships was the goal of a number of studies. The effect of induced acute supporting forelimb and hindlimb lameness on back kinematics has been the topic of several studies (Buchner *et al*. 1996a; Gómez Álvarez *et al*. 2007a, b; Pourcelot *et al*. 1998). These studies showed that even in case of a very subtle supporting limb lameness of forelimbs or hindlimbs, changes in thoracolumbar kinematics can be detected in the sagittal and horizontal planes (Gómez Álvarez *et al*. 2007a, b). Conversely, induction of even a moderately severe degree of back pain does not seem to immediately result in overt lameness, as was shown in a study in which the effect of back pain on horse motion was studied by injecting lactic acid into back muscles of trotters (Jeffcott *et al*. 1982). No major changes were found in linear and temporal stride parameters; only a stiffer back was noted. However, thoracolumbar kinematics was not quantified in any detail. In our parallel study, in this case with special attention to back kinematics (unpublished data), artificially induced unilateral back pain produced several changes in back motion, such as increased vertical range of motion, extension of the thoracic back, irregular thoracolumbar lateral bending and pelvic axial rotation to one side. These findings are in line with a study on patients with trunk ailments including chronic and acute muscle and bone pathologies in different locations of the vertebral column, in which several changes in motion of the back and pelvis were found (Wennerstrand *et al*. 2004). Temporal and linear stride parameters were not affected, but no detailed analysis of limb kinematics was performed.

Considering the intricate anatomical and functional connection between the back and the limbs we hypothesised that back pain would engender a detectable change in the kinematics of the limbs. To test this hypothesis we determined the kinematics and kinetics of the limbs in horses trotting on a treadmill before and after the induction of unilateral muscular back pain.

Materials and methods

Horses

Kinematics of the limbs was measured in eight sound Dutch Warmblood horses (age 11.7±4.9 years, height at the withers 163±3.6 cm, body mass 567±22.1 kg) while trotting (4.0 m/s) on a treadmill. The horses had been previously trained on the treadmill. The Experimental Animals Commission of Utrecht University had approved the experimental protocol.

Pain induction and subjective evaluation of back pain

Pain was induced by injecting a 85% lactic acid solution into the left *longissimus dorsi* muscle. Six locations were injected at approximately 10 cm from the midline at the level of the thoracic vertebrae T13, T14, T15, T16, T17 and T18, using a 21Gx1½" needle after clipping and disinfecting the area. The back was palpated regularly by a veterinarian during the experiment to evaluate muscle tension and pain.

Data collection

Measurements were performed using the infrared-based ProReflex® automated gait analysis system[1], operating at 240 Hz. Spherical infrared light reflective markers with a diameter of 19 mm were glued onto the skin overlying the scapular spine, the coxal tuberosity, and the centres of rotation of the shoulder, elbow, carpal, hip, stifle, hock and fetlocks joints. Markers were also placed on the lateral sides of all hooves and on the left wing of the atlas (Fig. 5.1). Markers were further located over the spinous processes of the following vertebrae: thoracic (T) 6, 10, 13 and 17; lumbar (L) 1, 3 and 5, and sacral 3 (S3). Six infrared cameras, situated three by three at both sides of the treadmill, recorded the marker coordinates while the horses were standing square and while they were trotting at 4.0 m/sec. The horses were recorded before the injections and 2 and 7 days after. For each session, data were captured for 10 seconds.

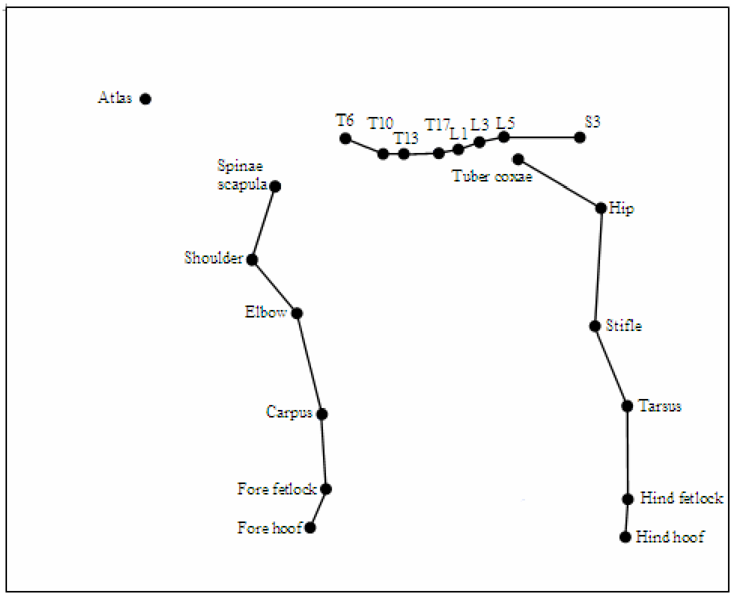

Figure 5.1. Diagram of a horse showing the locations of the skin markers used in this study (seen from left).

Data analysis

Qualisys Track Manager Software[1] was used to capture and process the data and Matlab® [2] was used for further analyses. Time was normalized to the duration of one stride cycle starting with the initial ground contact of the left hindlimb, as detected from the velocity profile of the limb.

Angles and stride parameters

Each joint angle was defined as the angle between three adjacent markers and was calculated in the three planes of a standard right-handed orthogonal Cartesian coordinate system. The angles of shoulder, elbow, carpal, hip, stifle, hock and fetlocks joints were determined. The angles of the shoulder, stifle and fetlock joints were defined by their caudal or palmar/plantar aspect and the angles of the rest of the limbs were defined by their cranial or dorsal aspect. The neck angle was calculated as the angle between a line connecting the markers on T6 and the atlas and the horizontal plane. Angular data was presented as maximal flexion and maximal extension. The inclination of the pelvis relative to the horizontal plane was calculated at both sides of the horse using the markers on the hip and the coxal tuberosity, and pelvic axial rotation was calculated using the markers on the coxal tuberosities and S3. Pelvic angular data was presented as maximal and minimal inclination and rotation. Stride duration and stride length were calculated using the marker on the hoof of the left hindlimb and presented as mean ± SD. Protraction-retraction (PR) angles were calculated using the markers on the hooves and T6 for the forelimbs, and S3 for the hindlimbs. PR data was presented as range of motion (ROM) ± SD, maximal protraction and maximal retraction.

Distances between limbs

The medio-lateral distance between the hooves was calculated using the hoof markers. Data was presented as maximal and minimal.

Limb position in relation to the vertebral column

The position of the limbs with respect to the vertebral column was defined as the medio-lateral distance between selected vertebral markers and each marker on the hooves. Data was presented as maximal and minimal.

Limb load calculation

In order to get an impression whether the induced back pain caused a change in the load distribution over the limbs, the total ground reaction force (GRF) and the vertical ground reaction forces on individual limbs were calculated from kinematics, as described elsewhere (Bobbert *et al.* 2007; McGuigan and Wilson 2003). Data was presented as mean ± SD.

Statistical analysis

Data were tested with Wilcoxon signed rank test. The level of significance for all tests was set at $p<0.05$.

Results

Clinical evaluation of back pain

Palpation 2 days after lactic acid injection showed moderate pain in the injected area and swelling at the injection sites. The horses were reluctant to stretch the painful side and they presented a slightly increased muscle tone. In the course of the week following the injections, muscle stiffness was apparent. After 7 days, there were no swellings at the injection sites and no sings of pain, but there was still an increased muscle tone and a reduced motion at the injected side of the back.

Limb joint angles

At day 2 there were no changes in joint angles when compared to the pre-injection values. At day 7 the maximal flexion angles of the left and right carpal joints, right stifle and left hock were decreased during the swing phase at day 7 (2.4, 3.2, 4.0 and 2.9º, respectively) (Fig. 5.2) (Table 5.1). Due to technical failure, the data captured from the markers on the right shoulder and right elbow could not be used.

Neck angle

There were no changes in the neck angle (Table5.1).

Pelvic inclination and axial rotation

The pelvis showed an increased leftward or anti-clockwise rotation (looking at the horse from behind) of 0.9º during the stance phase of the right hindlimb at both days 2 and 7 (Table 5.1, Fig. 5.2). There were no changes in pelvic inclination.

Stride parameters and protraction-retraction angles

Induction of unilateral back pain did not produce changes in stride duration, stride length or protraction-retraction angle of the limbs at any of the days (Table 5.1).

Distances between limbs

The minimum lateral distance between the fore hooves and between the hind hooves was increased 1.9 and 0.5 cm, respectively, at day 7 (Table 5.2).

Position of the limbs in relation to the vertebral column

The right hind hoof was located 1.2 cm more to the left with respect to L1 during the swing phase and the end of the stance phase at day 7. This was also the case with respect to L3 during the swing phase at day 7 (1 cm). The left hind hoof was also located 1.7 cm more to the left during the swing phase with respect to L1 at day 7 and, in relation to L3, 1.6 cm at day 2 and 1.8 cm at day 7 (Table 5.2).

Table 5.1. Maximal extension and maximal flexion of limb joints and neck (degrees); maximal and minimal rotation and inclination of the pelvis (degrees); maximal protraction, maximal retraction and protraction-retraction ROM of the limbs (degrees); stride length (m) and duration (sec) in horses (n=8) before, 2 and 7 days after induction of unilateral back pain.

Angle		Before pain induction	Post 2 days	Post 7 days	Stride phase where the differences occurred
Shoulder left	max extension max flexion	130.4 117.4	131.5 118.5	131.0 115.3	-------------------
Elbow left	max extension max flexion	152.4 104.5	150.5 103.5	151.2 104.4	-------------------
Carpus left	max extension max flexion	175.7 98.9*	175.7 100.3	175.5 101.3*	Swing phase LF
Fetlock fore left	max extension max flexion	232.7 186.6	232.4 187.5	232.4 187.1	-------------------
Carpus right	max extension max flexion	176.2 98.2*	175.8 100.3	175.7 101.4*	Swing phase RF
Fetlock fore right	max extension max flexion	231.4 185.7	229.6 186.2	230.8 185.8	-------------------
Hip left	max extension max flexion	120.7 94.9	120.5 95.1	120.9 95.7	-------------------
Stifle left	max extension max flexion	166.9 126.1	166.3 127.6	167.8 128.7	-------------------
Hock left	max extension max flexion	169.0 119.6*	168.7 121.8	169.2 122.5*	Swing phase LH
Fetlock hind left	max extension max flexion	233.7 183.0	234.6 183.9	234.2 183.6	-------------------
Hip right	max extension max flexion	120.9 94.6	121.5 95.5	121.7 95.9	-------------------
Stifle right	max extension max flexion	169.1 128.2*	170.2 131.2	170.6 132.2*	Swing phase RH
Hock right	max extension max flexion	169.6 120.4	169.9 122.4	170.1 123.9	-------------------
Fetlock hind right	max extension max flexion	237.2 183.4	236.2 183.7	236.2 183.4	-------------------
Neck	max extension max flexion	78.8 81.4	81.0 83.4	79.7 82.8	-------------------
AR left pelvis	max rotation min rotation	71.0 63.3	70.3 62.9	70.2 62.6	-------------------
AR right pelvis	max rotation min rotation	70.8* 63.8	71.7* 63.9	71.7* 63.8	Stance phase RH
Pelvic inclination left side	max inclination min inclination	67.8 62.1	67.5 61.9	67.4 61.6	-------------------
Pelvic inclination right side	max inclination min inclination	68.7 62.6	68.5 62.7	68.4 62.4	-------------------
Stride length	mean	2.6±0.1	2.6±0.1	2.6±0.1	-------------------
Stride duration	mean	0.7±0.0	0.7±0.0	0.7±0.0	-------------------

Protraction-retraction fore left	ROM	37.7±1.9	37.7±2.2	37.7±2.1	-------------------
	max protraction	22.1	22.1	22.1	
	max retraction	15.6	15.6	15.5	
Protraction-retraction fore right	ROM	37.7±1.9	37.6±2.6	37.6±2.7	-------------------
	max extension	21.9	21.9	22.1	
	max flexion	15.7	15.7	15.4	
Protraction-retraction hind left	ROM	37.6±2.7	37.3±1.7	37.0±1.2	-------------------
	max protraction	23.9	23.5	23.2	
	max retraction	13.8	13.8	12.9	
Protraction-retraction hind right	ROM	37.9±2.5	37.3±1.7	37.2±1.8	-------------------
	max protraction	23.6	23.1	23.0	
	max retraction	14.4	14.2	14.2	

* Statistically significant differences between before and after induction of back pain.

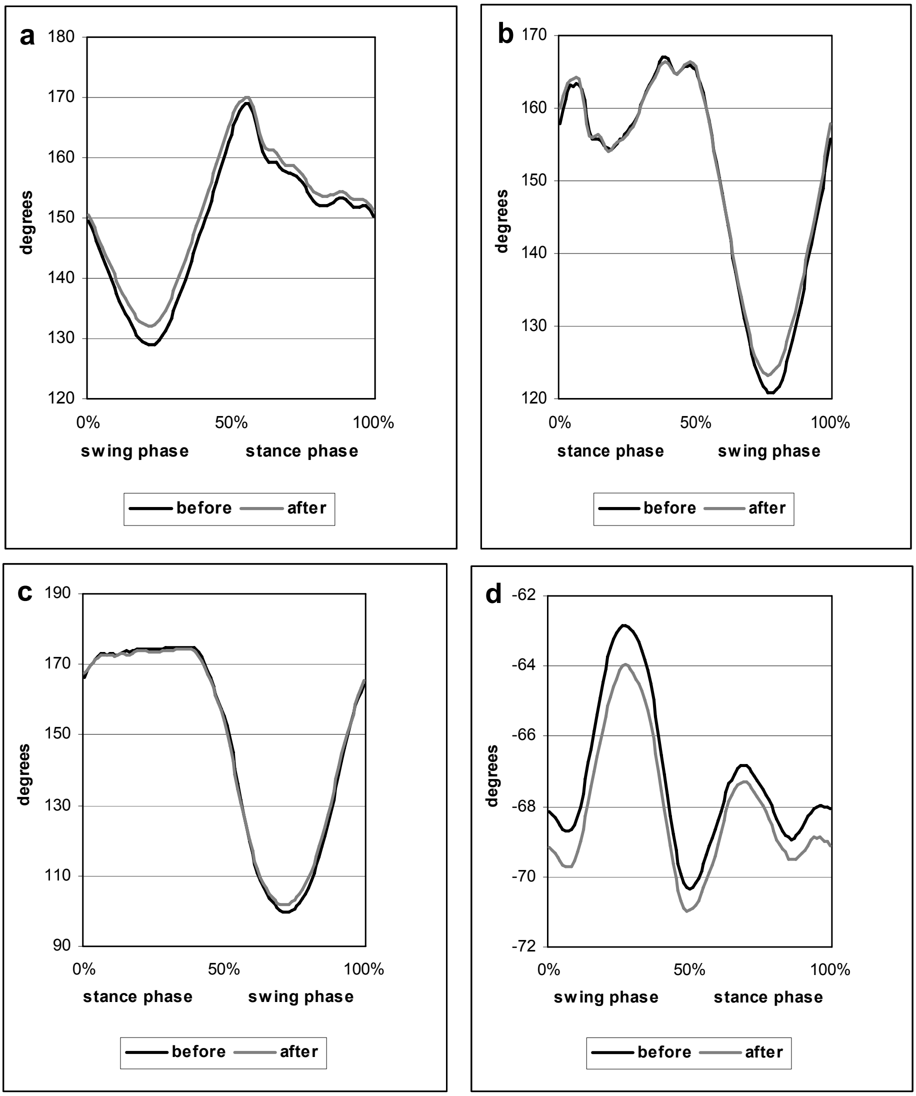

Figure 5.2. Mean (n=8) angle of a) right stifle, b) left hock, c) right carpus and d) pelvis (S3-right coxal tuberosity) before and after induction of back pain ($p<0.05$) at trot at 4.0 m/s.

The right fore hoof was located 1.6 cm more to the right with respect to L1 and 1.8 cm with respect to L3 during parts of the swing and stance phases (Table 5.2). There were no positional changes of the left fore hoof with respect to the vertebral column (Table 5.2).

Table 5.2. Maximal and minimal medio-lateral distances between the hooves and the vertebral column (cm); and between hooves (cm) in horses (n=8) before, 2 and 7 days after induction of unilateral back pain.

Segments		Before pain induction	Post 2 days	Post 7 days	Stride phase where max or min differences occurred
RF–LF hoof	max	32.4	31.5	31.7	First ¼ of swing phase and last ¼ of stance phase of RF.
	min	23.6*	24.1	25.5*	
RH–LH hoof	max	33.5	32.9	33.6	First ¼ of swing phase and last ¼ of stance phase of LH.
	min	21.6*	22.0	22.1*	
T6–RF hoof	max	17.0	16.8	17.3	-------------------
	min	10.6	10.9	11.0	
T6–LF hoof	max	18.2	18.0	17.9	-------------------
	min	11.0	11.3	11.8	
L1–RF hoof	max	15.7	15.8	16.4	Swing phase and last ¼ of the stance phase RF
	min	8.8*	9.8	10.4*	
L1–LF hoof	max	19.4	18.4	18.5	-------------------
	min	12.7	11.7	12.0	
L3–RF hoof	max	15.5	15.8	16.3	Last ¼ of the swing phase and during the stance phase RF
	min	8.5*	9.7	10.3*	
L3–LF hoof	max	19.6	18.5	18.6	-------------------
	min	12.9	11.6	12.1	
L1–RH hoof	max	20.5*	19.8	19.3*	Swing phase and last ¼ of stance phase RH
	min	8.7	8.8	8.9	
L1–LH hoof	max	17.7*	19.3	19.4*	Swing phase LH
	min	7.7	8.3	8.3	
L3–RH hoof	max	20.3*	19.8	19.3*	Swing phase RH
	min	8.6	8.8	8.9	
L3–LH hoof	max	17.9*	19.5*	19.7*	Swing phase LH
	min	8.0	8.3	8.5	

* Statistically significant differences between before and after induction of back pain.

Table 5.3. Calculated peak vertical ground reaction forces (GRF) of each limb (N/kg) in horses (n=8) trotting at 4.0 m/s before, and 2 and 7 days after induction of unilateral back pain.

Limb	Before	2 days after	7 days after
Right forelimb	11.9±0.7	11.9±0.9	12.0±0.7
Left hindlimb	9.7±0.5	9.8±0.5	9.6±0.4
Left forelimb	11.9±0.6	12.0±0.8	12.1±0.8
Right hindlimb	9.9±0.8	9.8±0.8	9.8±0.8

Calculated limbs loads

There were no significant changes in the calculated vertical ground reaction forces (GRF) of any of the limbs (Table 5.3).

Discussion

The results of this study confirmed the hypothesis that back pain, even if not severe enough to affect linear and temporal stride characteristics, produces changes in limb kinematics. The changes found correspond with those seen in thoracolumbar kinematics in our parallel study where the horses reacted by extending the thoracolumbar back and by bending to the painful side with an increased vertical range of motion of the vertebral column. The swing phase, in which the limbs are in flexion, requires flexion of the thoracolumbar back. We found that during the swing phase all limbs were flexed less while the back was more extended; in other words, the back was less able to flex and accomplish the proper suspension of the limbs. Limb flexion during the swing phase is partially a passive phenomenon due to the recoil of the elastic flexor tendons that store an elastic energy (Camp and Smith 1942; Dimery *et al.* 1986), but partly accomplished actively by the contraction of the flexor muscles. These muscles do not act as independent units, but form parts of a larger movement chain of interconnected muscle-tendon-bones between the head the back and the hindlimbs that includes trunk muscles and also the epaxial musculature. Functional impairment of one of the constituting elements of the chain will to a certain extent affect the others as well, which may be the reason why reduced limb flexion was a consistent finding in our horses with induced back pain. There is a parallel with clinical experience, as dragging of hindlimbs is an often-reported sign of (lumbar or iliosacral) back pain (Ross and Dyson 2003; Stashak 2002). The differences were relatively small, however, and did not result in changes in stride length and/or stride duration, which was in agreement with the study by Jeffcott *et al.* (1982).

The determination of the position of the hooves with respect to the thoracolumbar spine provided an insight in how the horse tries to adapt to the sore back. In the medio-lateral plane, both hindlimbs moved towards the painful side, probably following the direction of the back, which was bent to the same side (unpublished data), while the forelimb of the opposite side moved in the opposite direction of the hindlimbs, and the hindlimbs spread lightly, moving away from each other during periods of the swing and parts of the stance phases. However, these changes were rather small and might not be of great relevance.

Probably due to the very small and few changes found in limb kinematics during the stance phase, the peak vertical limb ground reaction forces and the linear stride parameters were not affected. In fact, most of the kinematic changes were observed when the limbs were not in contact with the ground. Less flexion of the limbs during the swing phase as found in this study will result in a less animated gait, which can be seen as a sign of back pain.

Most of the changes occurred 7 days after the pain induction and not at day 2, suggesting that they are related to the fair degree of muscle stiffness that came after the primary acute and painful episode. We may speculate therefore that horses might be more hampered in their natural movement by muscle stiffness than by acute muscle soreness.

We can conclude that back pain induces slight but systematic changes in limb kinematics. Although these changes are fairly subtle, it can be assumed that dragging of the limbs (or decreased flexion of the limb joints) can be interpreted as a sign of back pain.

Acknowledgements

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Manufacturers' addresses

[1] Qualisys Medical AB, Gothenburg, Sweden.
[2] Matlab® The MathWorks, Inc. Natick, MA.

Chapter 6

Spinal kinematics in horses with induced back pain

In preparation

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Summary

Reasons for performing the study: Back problems are important contributors to poor performance in sport horses. It has been shown that objective evaluation of the function of the back through kinematic analysis can differentiate horses with back problems from asymptomatic horses. The underlying mechanism can, however, only be identified in a uniform, experimental setting.

Objectives: To evaluate if inducing pain in a known tissue at a known localization within the back results in a consistent change in back movement.

Methods: Back kinematics was recorded in eight Warmblood riding horses at walk and trot on a treadmill. After the first measurement, unilateral back pain was induced by injecting lactic acid into the left *longissimus dorsi* muscle. Additional measurements were done during the week following the injections. Data were captured during steady state locomotion for 10 seconds at 240 Hz using an infrared-based automated gait analysis system. Vertebral range of motion and mean angles were derived from angular motion pattern data.

Results: During the week following the injections, the caudal thoracic back was more extended at both gaits ($p<0.05$). At trot, the back was also more bent to the left, while at walk it first bent to the left, followed by bending to the right ($p<0.05$). Additionally, the pelvis rotated more to the left shortly after the injections at both gaits and this rotation was still present after one week at trot ($p<0.05$). Flexion-extension range of motion (ROM) increased at some vertebral angles, but decreased in the lumbar region at trot ($p<0.05$). Lateral bending ROM had a large variability at both gaits.

Conclusions: Horses with identical back injuries appear to show similar changes in their back kinematics, as compared to the asymptomatic condition. Unilateral back pain results in an increased extension of the back, as well as compensatory lateral movements.

Possible clinical relevance: Back motion is complex and subtle, which makes it difficult for the human eye to detect changes. Present-day gait analysis systems can identify changes in back movement, and knowledge of the relationship between such changes and the site of injury will be of help in better localizing and diagnosing disorders of the equine back.

Keywords: equine; horse; vertebral kinematics; back pain, pain induction

Introduction

Equine back pain and dysfunction are common and important problems in veterinary medicine (Jeffcott, 1980). An exact diagnosis is however often hard to arrive at. Essential information can be obtained from the anamnesis and the clinical examination, but additional information is usually needed to correctly diagnose the patient. Frequently used techniques, such as regional anaesthesia, radiography, scintigraphy and ultrasound, are valuable diagnostic aids when evaluating a horse with back dysfunction, but sometimes they are insufficient to detect the origin of the problem. Earlier studies have shown that it is possible to measure objectively the movement of the back in detail (Audigié *et al.* 1999; Denoix 1999; Faber *et al.* 2000, 2001a; Haussler *et* al. 2001; Licka *et al*. 2001a, b). It has further been shown that sport horses with decreased performance, abnormal movements during work and clinical back pain on palpation show, at both walk and trot, a significantly decreased back movement compared to asymptomatic, competing riding horses (Wennerstrand *et al.* 2004).

It has been shown that back pain can be induced by the intramuscular injection of a concentrated (85%) lactic acid solution into the *longissimus dorsi* muscles (Jeffcott *et al.* 1982), which created a marked but reversible pain reaction with some heat and swelling resulting in some changes in stride parameters and increased stiffness of the back.

To interpret the changes in back motion properly, it is necessary to know how the changes correspond to the type and location of an injury. This can be accomplished by measuring the movement of the back in asymptomatic horses before and after inducing back pain in a specific tissue and location.

Our hypothesis was that induction of back pain in a well-defined site results in a corresponding consistent change in back kinematics. In this study we determined vertebral kinematics in horses trotting and walking on a treadmill before and after back pain induction.

Materials and methods

Horses

Eight Warmblood horses, all mares, between 7 and 12 years old were used in this study. Mean body mass was 567±22.1 kg and mean height at the withers 163±3.6

cm. All horses were in regular training for dressage or show jumping, and two were also sometimes used for driving. The horses underwent a clinical examination, including a visual and palpatory examination, observation of the horse moving in hand on a hard surface and lunging at both reins. Flexion tests were done on all four limbs. If lameness was detected or a horse demonstrated pain on palpation of the back, it was excluded. Back pain was considered present if the horse showed signs of pain/discomfort on palpation of the back.

Experimental set-up and data collection

Prior to the first recording the horses were trained at several occasions on the treadmill at both gaits to ensure a consistent gait pattern (Fredricson *et al.* 1983; Buchner *et al.* 1994). Back and limb kinematics was measured at walk and trot on a treadmill before and at 1 hour, 1 day, 2 days, 3 days and 7 days after the pain induction. Spherical, reflective markers, 19 mm in diameter, were glued onto the skin over the dorsal spinous processes of the thoracic vertebrae (T): T6, T10, T13, T17; lumbar (L): L1, L3, L5 and sacral (S) S3. Markers were also placed on both left and right coxal tuberosities and proximally on the lateral part of the hoof wall of each hoof. Extra markers were placed on the limbs for a parallel study. The landmarks were identified by palpation in the square standing horse. The positions of the markers were captured by six infrared cameras (ProReflex®)[1], which were positioned around the treadmill in a way that each marker was always seen by at least two cameras. Measurements were made relative to a right-handed orthogonal laboratory coordinate system with the positive y-axis oriented in the line of progression, the positive z-axis oriented upward and the x-axis oriented perpendicular to the direction of the y- and z-axes. Data were captured at a sampling rate of 240 Hz for 5 seconds at square stance and for 10 seconds with the horses walking (1.6 m/s) and trotting (4.0 ms$^{/}$s) on the treadmill.

Injection technique

Each horse stood unsedated in a quiet room. The back was clipped and aseptically prepared. The dorsal spinous processes of T13, T14, T15, T16, T17, T18 and L1 were identified by palpation. Two ml of 85 % lactic acid solution was injected into the left *M. longissimus dorsi* at the height of the caudal edges of T13, T14, T15, T16, T17 and T18, approximately 10 cm left of the midline using a 40 mm long, 21 gauge needle. Total volume injected was thus 12 ml.

Calculation of back kinematics in 3D

The reconstruction of the 3-dimensional position of each marker is based on a direct linear algorithm (QTrack™)[1]. The x-, y- and z-coordinates were exported into

MatLab®[2] and Backkin®[1] programme packages for further data processing. The beginning of each stride cycle was defined from the velocity profile as the moment of first ground contact of the left hind hoof. The x-, y-, and z-coordinates were used to calculate the flexion-extension, lateral bending and pelvic axial rotation in accordance to Faber *et al*. (1999). An explanation of the principles of the instantaneous orientation of a vertebra has been presented by Johnston *et al*. (2002). Coordinates were extracted at walk and trot from approximately 8 and 10 representative strides, respectively. Angular motion patterns (AMPs) were calculated for each vertebral angle and were normalised to the stride. Stride length and duration were calculated from the marker on the left hind hoof. The total range of motion (ROM) was derived from the AMPs.

Statistical analysis

All results are presented as means ± SD. Data were tested for normality of distribution. The variations in the vertebral angles throughout the stride were normally distributed and further analysed with matched pairs t-test. Wilcoxon matched pairs was used to test mean AMP and ROM. The level of significance was set to $p<0.05$.

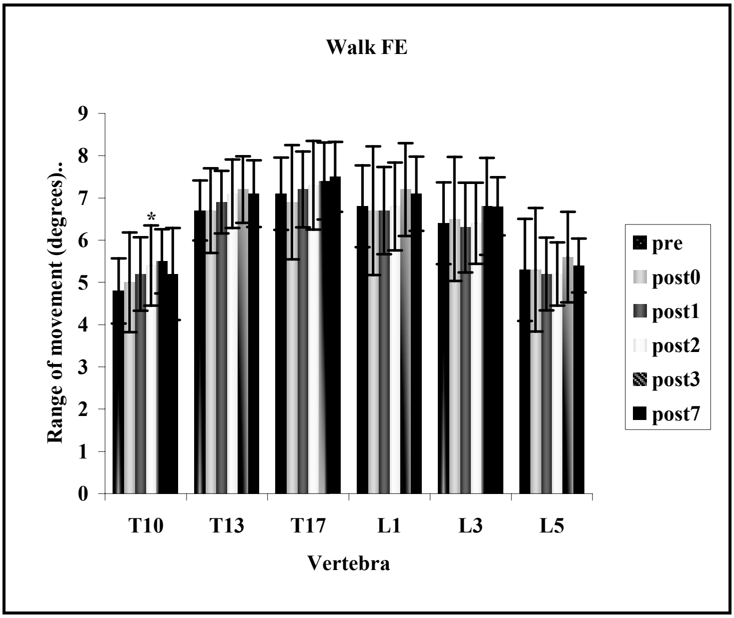
Ethical Review

The Experimental Animals Commission of Utrecht University had approved the experimental protocol.

Results

Clinical signs

Subsequent to the lactic acid injections, the horses demonstrated mild to moderate pain on palpation of their backs during a few days. One hour after the injections, mild swelling had appeared in some of the horses. The injected areas were also mildly to moderately painful. Twenty-four hours after the injections, the injection sites were swollen in all horses, with a maximum diameter of 5 cm. On palpation, 4 of the horses demonstrated mild pain in the left half of the caudal thoracic back. Due to technical circumstances, the other four horses were not palpated 24 hours post injection. The swelling peaked at 48 hours after the injections, with diameters up to 10 cm around the injection sites. At that time, 6 of the horses were mildly and 2 moderately painful left to the mid-line in the region from the withers to the mid-lumbar back. Three days after the pain induction, most swellings had started to decrease.



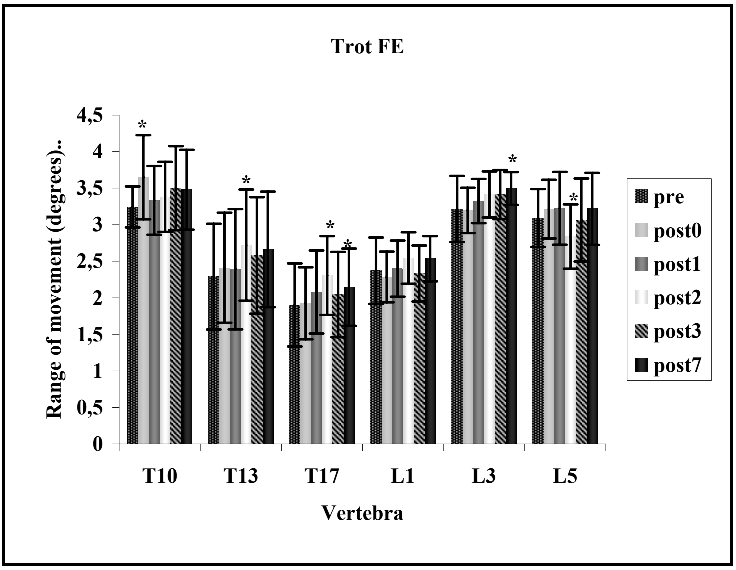


Figure 6.1. Mean flexion-extension ROM ± SD (degrees) of six vertebral angles at walk (top) and trot (bottom) of 8 horses. Bars represent the measurements in the following order: pre injections (pre), 1 hour post injections (post 0), 1 day post injections (post 1), 2 days post injections (post 2), 3 days post injections (post 3), 7 days post injections (post 7). *Statistically significant differences ($p<0.05$) between before and after induction of back pain.

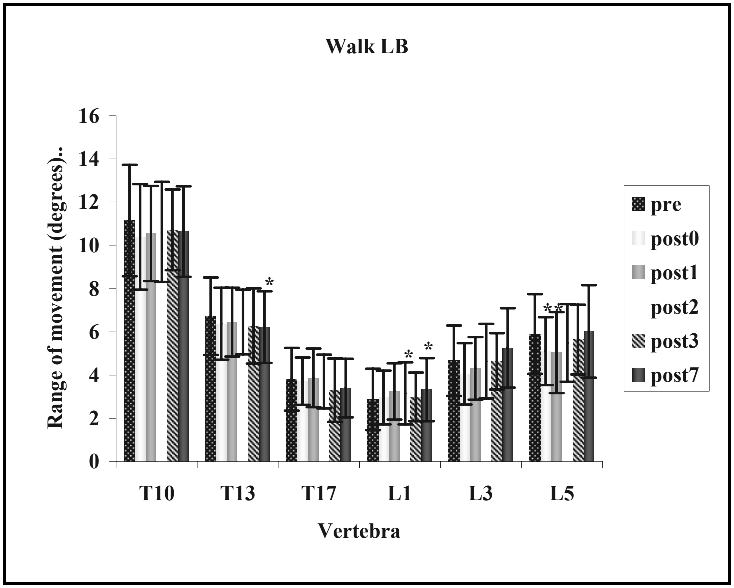
The left *M. longissimus dorsi* was still mildly to moderately painful from T13 to the thoracolumbar (T/L) junction in all 8 horses. Two of them also demonstrated pain on palpation of the cranial lumbar back. After one week, most swellings had reduced to barely visible or only palpable. A few swellings remained, the largest with a diameter of 2 cm. On palpation of the back no abnormality was noted in 2 horses; 6 horses had stiff back muscles or a mildly tense skin. Of these 6, 5 were not painful at all, and the last one was painful only from T12 to T14.

Range of motion (ROM)

Flexion-extension: Changes in range of motion were observed throughout the entire week following the injections. One hour after the pain induction, the flexion-extension ROM was increased by 0.5º at T10 at the trot. Two days after the injections, the flexion-extension ROM was increased 0.6º at T10 during walk; it was also increased in the caudal thoracic and lumbar back at the trot (T13=0.4º, T17=0.4º'), while it was decreased 0.3° at L5 at the same gait. Three days following the injections, the flexion-extension ROM at T13 was still 0.3° increased at trot. One week after the horses had been injected, most of them were no longer painful on palpation, but at trot the flexion-extension ROM was still increased in the caudal thoracic back (T13=0.4º, T17=0.3º) and in the lumbar back (L3=0.3º) (Fig 6.1).

Lateral bending: At walk, the lateral bending ROM was reduced 0.7º at L5 one hour after the pain induction and 1.0º after 24 hours. At trot, the lateral bending ROM was decreased 0.8º at T10 the day after the injections and 0.9º two days after. Two days following the injections, the lateral bending ROM increased 0.3º at L1 at walk, while it decreased 0.3º at trot. The lateral bending ROM at L1 at walk was increased 0.6º still after one week. A decreased range of motion of 0.4º was observed at T13 at walk after one week (Fig 6.2).

Axial rotation: No significant change was observed in axial rotation ROM of the pelvis after the injections at walk or trot.



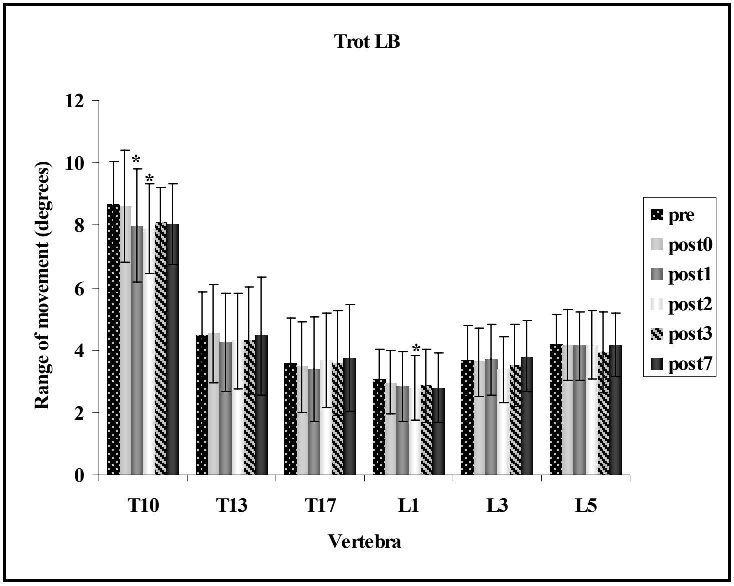
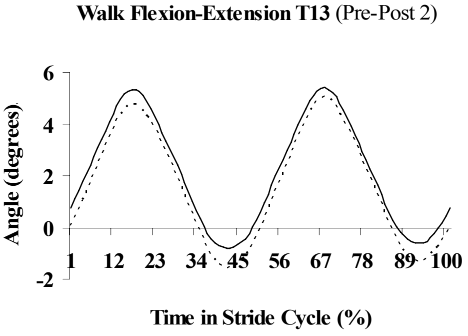
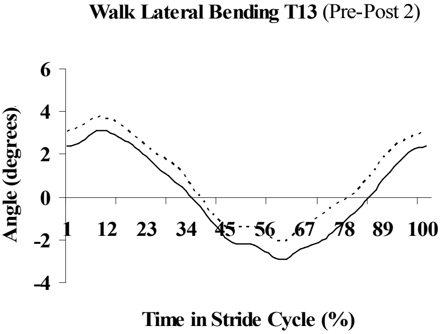


Figure 6.2. Mean flexion-extension ROM ± SD (degrees) of six vertebral angles at walk (top) and trot (bottom) of 8 horses. Bars represent the measurements in the following order: pre injections (pre), 1 hour post injections (post 0), 1 day post injections (post 1), 2 days post injections (post 2), 3 days post injections (post 3), 7 days post injections (post 7). *Statistically significant differences ($p<0.05$) between before and after induction of back pain.





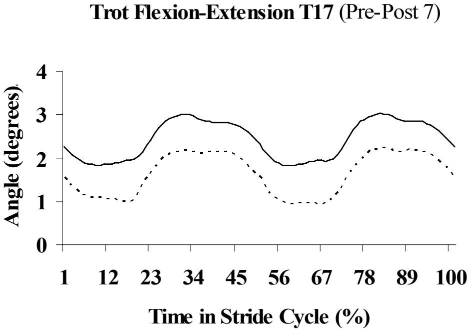


Figure 6.3. Flexion-extension and lateral bending motion of the vertebral angles: T10-T13-T17 (top) and T13-T17-L1 (middle) at walk; and flexion-extension at T13-T17-L1 (bottom) at trot, normalized to one stride cycle in one horse after pain induction. Solid line: pre injections (pre); dotted line: 2 days post injections (post 2). Positive is flexion or bending to the left and negative is extension or bending to the right.

Vertebral angular motion patterns

During the week following pain induction, the vertebral flexion-extension and lateral bending and the pelvic axial rotation changed significantly compared to before the injections at both gaits (Fig 6.3).

At trot, there was an increased extension during the entire stride cycle at T10 (increase of 1.0° at day 2, 1.1° at day 3 and 0.9° at day 7 after pain induction); at T13 (0.8° at day 3 and 0.7° at day 7); and at T17 (0.6 ° at day 1, 0.5° at day 2, 0.7° at day 3 and 0.8° at day 7). There was an increased flexion at L5 of 0.3° at day 3 and 0.4° at day 7 during hoof contact of the left hindlimb. T10, T17 and L5 were bent to the left during the entire stride cycle (T10: 1.1° at day 2 and 1.0° at day 7; T17: 1.1° at day 7; L5: 1.0° at day 2 and 1.0° at day 7). The pelvis was 0.7° more rotated to the left during hoof contact of the left hindlimb one hour after induction of pain and 0.5° during the left diagonal at day 7.

At walk, there was also an increased extension during the whole stride at T10 (increase of 1.5° one hour after pain induction and 0.9° at day 3) and at T13 during the stance phases of both left limbs (0.6° at day 2, 0.6° at day 3 and 0.5° at day 7). The direction of lateral bending changed over the days. T10 was 1.3° bent to the right during the whole stride at day 7; T13 was 0.7° bent to the left during the whole stride at day 2 and 0.6° to the right during the stance phases of both left limbs at day 7; T17 was 1° bent to the left during the whole stride at day 2 and 1.3° to the right during both left stance phases at day 7 post injections; L5 was 1.2° bent to the right during the whole stride at day 7. The pelvis was 0.8° more rotated to the left during the stance phase of the right forelimb 1 hour after the pain induction.

Linear and temporal stride parameters

There were no statistically significant changes in the linear and temporal stride parameters. The stride length was 2.6±0.1 meters (m) at all days at trot and 1.8±0.1m at all days at walk, except at one hour after the pain induction where the stride length was 1.7±0.1m. The stride duration was 0.7±0.0 seconds (s) at all days at trot and 1.1±0.1s at all days at walk, except at 2 and 7 days after pain induction where it was 1.1±0.0s.

Discussion

The results of the present study confirm our hypothesis that back pain in a well-defined site results in significant and consistent changes in vertebral kinematics.

Lactic acid injected into the *M. longissimus dorsi* has been used earlier as a model for reversible back pain and was shown to cause a mild spontaneous pain at walk and trot (Jeffcott *et al.* 1982). In that study, there were no changes in stride parameters but a decreased level of performance and a stiffer back was noted. Two studies with patients have shown that horses with back pain have an aberrant movement pattern of the back, which is in accordance with our findings (Faber *et al.* 2003; Wennerstrand *et al*. 2004). However, in one of those studies (Wennerstrand *et al*. 2004), the horses showed a decreased range of flexion-extension motion at the caudal thoracic back and T/L-junction, which is opposite to our present findings.

In our study, back pain was clearly evident in all horses subsequent to the injections. Whereas no abnormal back movements could be detected by clinical observation, the kinematic analysis revealed several. The increased extension of the caudal thoracic back may be due to a shorter and stiffer *longissimus dorsi* muscle not being able to stabilize the vertebral column. However, the stiffness is not reflected in a decreased ROM, but shows as a clearly increased motion. This can be due to the fact that the induced back pain was unilateral; the compensatory mechanism can be assumed to be different between bi- and unilateral back pain with bilateral back pain being more likely to induce a restriction of movement of the entire back.

From this study and the earlier work by Jeffcott *et al.* (1982) it becomes clear that back pain, even when this is clinically obvious, will not easily affect linear or temporal stride characteristics. This does not mean, however, that there is no influence on limb kinematics, as significant changes in angular motion pattern of various limb joints could be demonstrated in a parallel study (Gómez Álvarez *et al.* 2007c).

The back was expected to bend asymmetrically due to the unilateral induction of pain. The increased horizontal lateral bending most likely is a consequence of the lack of muscle function at the painful side. Loss of tension in the painful epaxial musculature may disturb the naturally existing left/right balance and lead to a scoliosis of the back with, in this case, right convexity as a result of loss of muscle function at the left side. After some days, the horses showed a reverse pattern, *i.e.* bending towards the non-affected side. This is probably caused by stiffening of the injected muscle, which may not be able to properly contract anymore. This biphasic response was also observed in the earlier study in trotters with induced back pain (Jeffcott 2007, personal communication).

From the clinical examinations it became clear that the horses had painful backs during the first days but became much stiffer after some days. Most changes appeared 48-72 hours post injections. Muscle soreness after high intensity exercise occurs during or immediately after exercise, caused by increased lactic acid accumulation in the tissue. However, 24-48 hours after exercise there is another, sometimes more severe, peak of soreness accompanied by stiffness, which in human medicine is called delayed onset muscle soreness (DOMS) (Marlin and Nankervis 2002). It seems that a similar phenomenon occurred after the injection of lactic acid in the horses of our study, in which the increased stiffening after a couple of days may represent the natural second peak of muscle pain. There was also a direct effect, as a few changes could be also observed immediately after the injections. Given the nature of lactic acid, there was an acute pain reaction. In naturally occurring muscle pain, this acute soreness is due to the lactic acid itself, the effect of hydrogen ions that are produced and oedema due to fluid uptake into the interstitial spaces (Marlin and Nankervis 2002). In the artificially induced back pain in this study, there were some differences with the natural situation. Whereas the total volume of fluid may even have been comparable to the naturally occurring oedema, the fluid was in this case administered as a single bolus and there was no gradual built-up. It has been shown that injection of a certain volume of liquid *per* se also influences back motion, presumably by its effect on propriocepsis (Roethlisberger-Holm *et al*. 2006).

In general, back movement changes in a comparable way at walk and trot. There were only some differences in the horizontal plane. At both gaits, the back was generally more bent to the painful side. This asymmetry was most evident at trot. It is known that back muscle activity is normally greater at trot than at walk, where the swinging motion of the back at walk is largely passive (Robert *et al*. 1998); it lies at hand therefore that muscle soreness will affect back motion more, and will remain manifest for a longer period, at trot than at walk.

Back movements in the horse are subtle and complex, and different injuries will affect back motion patterns in various ways. In this study just one, artificially induced lesion was analysed, but the study shows that with present-day technology we can detect movements and changes therein that are undetectable for the human eye.

Although kinematic analysis of equine gait has, for several reasons, never brought the dramatic improvement of lameness diagnosis it once was thought it would (van Weeren 2002), it seems to have a marked added value in the case of the analysis of equine back motion where the human eye is insufficient to detect all but very gross changes. Modern kinematic analysis seems an adequate tool, therefore, to help in the demystification of back problems in the horse and in putting to the test the large number of sometimes scientifically very questionable therapies that are advocated for their treatment. To achieve this, prospective studies in relatively large cohorts of animals are needed, including blinded studies into various treatment modalities with long-term follow-up.

Manufacturers' addresses

[1] Qualysis Medical AB, Gothenburg, Sweden
[2] Matlab® The MathWorks, Inc. Natick, MA.

Acknowledgements

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Chapter 7

Effect of chiropractic manipulations on the kinematics of back and limb in horses with clinically diagnosed back problems

Under revision

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Summary

Reasons for performing the study: Chiropractic treatment is one of the most commonly used therapies for the treatment of back pain in horses. Although there is anecdotal evidence of clinical effectiveness, little scientific work has been done on the subject.

Objectives: To quantify the effect of chiropractic manipulations on back and limb kinematics in horse locomotion.

Methods: Kinematics of 10 Warmblood horses was measured over-ground at walk and trot at their own, preferred speed before, and 1 hour and 3 weeks after chiropractic treatment that consisted of manipulations of the back, neck and pelvic area. Speed was the same during all measurements for each horse.

Results: Chiropractic manipulations resulted in increased flexion-extension range of motion (ROM) ($p<0.05$) at trot in the vertebral angular segments: T10-T13-T17 (0.3°) and T13-T17-L1 (0.8°) 1 hour after treatment, but decreased ROM after three weeks. The angular motion patterns (AMPs) of the same segments showed increased flexion at both gaits 1 hour after treatment (both angles 0.2° at walk and 0.3° at trot, $p<0.05$) and 3 weeks after treatment (1.0° and 2.4° at walk and 1.9° and 2.9° at trot, $p<0.05$). The lumbar (L3 and L5) area showed increased flexion after 1 hour (both angles 0.3° at walk and 0.4° at trot, $p<0.05$) but increased extension after 3 weeks (1.4° and 1.2°, at trot only, $p<0.05$). There were no detectable changes in lateral bending AMPs. The inclination of the pelvis was reduced at trot 1 hour (1.6°) and 3 weeks (3°) after treatment ($p<0.05$). The mean axial rotation of the pelvis was more symmetrical 3 weeks after the treatment at both gaits (1.4±6.0° before treatment and 0.1±4.7° after 3 weeks at walk; and 1.6±3.1° before treatment and -0.3±3.4° after 3 weeks at trot, $p<0.05$). At trot, the protraction of the forelimbs was decreased by 4.8° and 4.4° (right and left respectively) 1 hour after the treatment, and 4.7° (right) after 3 weeks. One hour after treatment the protraction of the hindlimbs was decreased by 5.9° and 6.0° (right and left, respectively) and the retraction by 5.3° and 5.5° (right and left, respectively); after 3 weeks, changes were only found on the left side (protraction reduced by 3.6° and retraction by 3.1° at trot). There were no changes in limb angles at walk and almost no changes at trot ($p>0.05$).

Conclusions: The main overall effect of the chiropractic manipulations was a less extended thoracic back, a reduced inclination of the pelvis, improvement of the symmetry of the pelvic motion pattern and a more physiologic reduced maximal protraction and maximal retraction.

Potential relevance:
Chiropractic manipulations elicit slight but significant changes in thoracolumbar and pelvic kinematics. These changes are likely to be beneficial, but clinical trials with increased number of horses and longer follow-up are needed to determine clinical effectiveness unequivocally.

Keywords: Back kinematics, limb kinematics, horses, chiropractic treatment, back pain, back problems.

Introduction

Back problems or alleged back problems are not a new phenomenon in horses (Lupton 1876), but they certainly are reported more frequently nowadays (Ross and Dyson 2003). Whether this apparent increase in incidence is due to the changes in the use of horses over the past decades, or in fact is biased because of a better awareness within the equine community of the existence of back problems is unclear, but it is a fact that the present-day equine orthopaedic practitioner is often confronted by these challenging cases. Equine back patients are difficult patients in both a diagnostic and therapeutic sense because of the relative inaccessibility of the huge structures that make up the equine back and the lack of objective criteria that can be used to define back movement and monitor the effect of interventions. These conditions, and the lack of responsiveness of many back patients to traditional medication-based treatments alone, have fomented the application of many alternative remedies and integrative treatments in equine back patients.

Among the more frequently used complementary therapies are various techniques that rely on direct or indirect manual manipulation of segments of the equine spine. Chiropractic manipulations, which is defined as a high-velocity, low-amplitude (HVLA) manual thrust (Haussler 1999), is one of the most commonly used techniques. Chiropractic treatment aims at the resolution of musculoskeletal disorders that are induced by biomechanical factors. The benefits that are claimed for the chiropractic treatment of equine back disorders include improvement of the vertebral symmetry by restoring normal joint motion in one or more planes (reversing hypermobility or hypomobility), restoring normal pain sensation (by inhibition or facilitation), and improving altered (muscle, connective, vascular) tissue function (Haussler, 1999). The effectiveness of chiropractic manipulations has been widely documented in human medicine (Eisenberg *et al.* 2007; Gaumer

2006; Hurwitz *et al.* 2006; Leaver *et al.* 2007). Although there is abundant anecdotal clinical evidence on the effectiveness of chiropractic techniques in horses, the scientific research in this area has been limited to studies using relatively few horses (Haussler *et al.* 1999) , or only a single case in which another form of manipulative technique was used (Faber *et al.* 2003).

The close relationship between back and limb function has been investigated in some field studies. Landman *et al.* (2004) found lameness and concomitant back pain in 26% of the horses from a population of 805 patients that were presented with orthopaedic problems, and Dyson (2005) observed concurrent forelimb and hindlimb lameness in 46% of horses with thoracolumbar or sacroiliacal pain. Recent experimental studies into this field showed the intricate link between back and limb kinematics. Artificial induction of reversible back pain by the injection of lactic acid did not lead to changes in temporal or linear stride characteristics in either trotters (Jeffcott *et al.* 1982) or Warmbloods (Gómez Álvarez *et al.* 2007c), but it caused statistically significant changes in both back kinematics (Wennerstrand, unpublished results) and in angular limb kinematics (Gómez Álvarez *et al.* 2007c). In a reverse sense, induction of even a very subtle lameness in either forelimbs or hindlimbs had a statistically significant effect on thoracolumbar kinematics (Gómez Álvarez, 2007a, b), giving support to the clinical impression that chronic subclinical lameness may be implicated in the pathogenesis of back dysfunction. Because of the intricate relationship between back and limb function, attempts to quantify the effect of any proposed treatment for back disorders should ideally try to asses the effects on both thoracolumbar and limb kinematics.

The present study aims at the quantitative assessment of the effect of chiropractic manipulations on back and limb kinematics. The hypothesis to be tested was that chiropractic manipulations will affect both thoracolumbar and limb kinematics in the sense that they improve vertebral movement and enhances symmetry of pelvic motion in horses with back problems, thus altering the motion pattern towards a more normal [and symmetrical] pattern. For this purpose, we determined the kinematics of the vertebral column and the limbs in back pain patients at walk and trot before and after chiropractic manipulations.

Materials and Methods

Horses

The patient population consisted of 10 Warmblood horses (12.8±6.3 years of age, height at the withers 1.69±0.05 cm, and body mass of 640±53.3 kg). These horses were selected from horses presented for various reasons to a three-person veterinary practice located in Northern Germany, specialised in, and performing only, equine chiropractic manipulations (n=6), and from horses used by the Dutch Veterinary Student Riding Association (n=4). Both groups were treated and measured in their respective location. All horses underwent clinical and chiropractic examinations by a qualified veterinarian with formal training in equine chiropractic techniques. Horses were selected on the presence of signs of back pain and/or dysfunction, and the absence of lameness. The animals included in the study were those considered to have greater than normal sensitivity over the thoracolumbar region upon examination (Table 7.1). Such horses can be described as typically "sore-backed" horses seen by veterinary chiropractors on a regular basis. Patients with signs of lameness or considered as having a very poor prognosis, regardless of the therapy chosen, were excluded. The Committee on the Ethics of Animal Experiments of Utrecht University had approved the experimental protocol.

Chiropractic manipulations

The chiropractic techniques employed in this study are based originally on those widely used in human chiropractics, which have been adapted to the equine anatomy over the past twenty years. Following a chiropractic examination assessing joint motion of the entire body, the treatment consists of high velocity, low amplitude (HVLA) thrusts, directed at very specific directions, in accordance with the anatomy of the joint(s) being treated. These manipulations, or "adjustments", are intended to restore the normal range of motion of the joints. The techniques are those used by the majority of veterinarians in both Europe and North America who have received formal training and are practicing veterinary chiropractic manipulation techniques. These are the techniques promoted and recognised by both the International Veterinary Chiropractic Association (IVCA) and the American Veterinary Chiropractic Association (AVCA). All treatments were performed by one of two qualified veterinarians. After the treatment, horses were hand-walked for around 10 minutes.

Table 7.1. Description of the vertebral and pelvic chiropractic findings in 10 patients with back pain/dysfunction included in this study. FE: flexion-extension; LB: lateral bending; C: cervical; T: thoracic; L: lumbar; SI: sacroiliac; I: ilium, TM: temporo-mandibular; *r*: right; *l*: left; *s*: superior; *p*: posterior. Pain/sensitivity scale (1-5): 5 is higher score of pain. Motion scale (1-5): 5 is bigger motion.

Patient	Pain/sensitivity (1-5) and location	Motion (1-5) and location	Location of spinal segmental dysfunction	Location of other relevant dysfunctions/ subluxations
1	1 in the whole back bilateral	FE 1 and LB 2 from T18-L4	C1 *rs*, C2 *p*, C4 *rp*, C4-5 *l*, T9-16 *d*, L1-4 *d.*	Both SI joints
2	2.5 in T10-L4 bilateral	3 from T10-L4.	C1 *rs*, C2 *p*, C4 *r*, T5-8 *l*, T12-14 *ld*, L3-6 *d*.	Asymmetric motion of the pelvis. Right SI joint. TM joint.
3	3.5 T13-T17 bilateral	3.5 T13-L4	C4 *r*, T7 *l*, L1 *d*, L2 *d*.	Bilateral pain in the costo-vertebral joints. SI right side.
4	2 in the whole back bilateral	2 in the whole back	C1 *ls*, C5 *l*, T16-18 *ld*, L3-4 *rd,* L5 *d*.	Right SI joint. TM joint.
5	2 in the whole back bilateral	2 in the whole back	C6 *l*, T10 *d*, L5-6 *lr*.	Right SI joint
6	1 in the whole back bilateral	4 in the whole back	C1 *rp*, C3 *l*, T18 *d*, L2 *ld,* L3-4 *rd*.	Back extremely bent to the left. Left SI joint. TM joint.
7	3 from T7-12 bilateral	5 in the thoracic back	C1 *lp,* C3 *l,* T6-11 *l,* T16 *l,* L2-5 *d*.	Caudal extreme of sacral bone more to the left.
8	2.5 T10-L5 bilateral	4 in the neck from C1 to C5 bilateral	C1 *rp,* C2 *p,* C3 *l,* C5 *r*, T1-9 *l*, T15-17 *rd,* T17-L5 *d*.	Kyphosis L1-5. Epaxial muscle atrophy T10-L4 bilateral.
9	1 in the whole back bilateral	5 in the whole back	C1 *rp ls*, C4 *l*, T8 *l*, T13-14 *d*, T16-17 *ld*, L2-3 *ld*, L5 *rd*.	Short stride length right hindlimb. Right SI joint.
10	4 from T16-17 bilateral	3 in the whole back	C1 *rp*, T8 *l*, T16-17 *rd*, L3 *d*.	Right SI joint. Caudal extreme of sacral bone more to the left.

Data collection

Kinematic measurements were performed with the horses walking and trotting over-ground. The surface consisted of either tarmac or gravel, depending upon the location. Measurements were done before the treatment, immediately after and 3 weeks after the treatment for short-term and long-term assessments. Markers placement was documented by photography and written description for each horse in order to accurately asses the same locations between measurements. The effects of the chiropractic interventions were assesed by kinematic measurements and by subjective reports of the owners/trainers, based on the athletic performance of the horses and on other observations. For the kinematic data collection the infrared-based ProReflex® automated gait analysis system[1] was used at 240 Hz. Spherical infrared light reflective markers with a diameter of 19 mm were glued to the skin over the spinous processes of thoracic vertebrae 6, 10, 13 and 17 (T6, T10, T13, T17), the lumbar vertebrae 1, 3 and 5 (L1, L3, L5), the 3rd sacral vertebra (S3) and left and right sacral tuberosities. Markers were also placed on the lateral side of the left limbs on the centres of rotation of the shoulder, elbow, carpal, hip, stifle, hock and fetlock joints; and on the left coxal tuberosity. Markers were also placed on the medial side of the right hooves and on the left wing of the atlas (Fig. 7.1). Six infrared cameras situated at one side of the track recorded the marker locations while the horses were standing square and at walk and trot. Recordings were made at the individual horse's preferred speed. Speed was calculated from the distance covered and the time required recorded with a laser chronometer. Recordings were repeated until obtaining the same speed for a given individual horse.

Subjective evaluation

Questionnaires were given to the owners/riders to obtain information about their observations of the horses before and after the treatment. The questions were divided over 5 sections: general, back, head and neck, limbs and attitude. Pain and motion were described using a semi-quantitative scale of 1 to 5, with 5 being the most painful or the biggest motion.

Data analysis

Qualisys Track Manager Software[1] was used to capture and process the data and Matlab®[2] for further analyses. A standard right-handed orthogonal Cartesian coordinate system was used to describe the motions. Vertebral motion was described as flexion-extension (in the sagittal plane), lateral bending (in the horizontal plane), and axial rotation of the pelvis (in the transversal plane). All the vertebral movements were calculated using Backkin® [1] and presented as angular motion patterns (AMP) during the stride cycle. The range of motion (ROM) was calculated for each AMP and was defined as the difference between maximal and minimal values of the AMP. Data captured in the square standing horse were used to determine the zero (reference) value in the AMPs in each horse. The vertebral angles were defined as the angle between three adjacent marked vertebrae (e.g., the angle at T10 is the angle between the line from T6 to T10 and the line from T10 to T13). The beginning of each stride cycle was taken to be the initial ground contact of the left hindlimb. The angles calculated in the left limbs were for the shoulder, elbow, carpal, hip, stifle, hock and fetlock joints. Pelvic inclination was calculated with the markers on the left hip and left coxal tuberosity. Pelvic axial rotation was calculated with the markers on the left and right sacral tuberosity and S3. For the graphical representation of pelvic axial rotation, the linear trend in each curve was determined and represented by straight line as the relative position in the stride cycle of the intersection of this line with the zero axis is an indication of symmetry of movement. The neck angle was calculated as the angle between the markers on T6 and atlas and the horizontal plane. Stride length was calculated from the marker on the left hind hoof. Protraction-retraction angles were calculated for the limbs using the markers on the hooves and T6 for the forelimbs, and the hooves and S3 for the hindlimbs.

Statistical analysis

The distribution of values for kinematic variables was tested for normality. If normally distributed, analysis was carried out using ANOVA for repeated measures and a Bonferroni correction. If data were not normally distributed a Wilcoxon signed rank test was used. The level of significance was set at $p<0.05$.

Results

Chiropractic manipulations

The chiropractic manipulations were all carried out to the satisfaction of the treating veterinarian in all horses, with no signs of distress or any other adverse side-effects noted in any of the treated animals.

Subjective evaluation

The veterinarian evaluated the treatment results as effective for each horse, based on his assessment of spinal mobility at the conclusion of the treatment. According to the opinion of the owners/riders of the treated horses expressed on questionnaire, the horses varied in their reactions to the treatment, *i.e.* after the treatment five horses had no back or neck pain anymore, or sensitivity had decreased considerably. Five horses had a better motion of the back or neck; five were reported to have a longer and easier stride length; three horses were described as “feeling happier and more relaxed”. Three horses showed temporary (from day 2 to day 10 after the treatment) muscle pain in the back and two horses showed slight lameness, but these two horses were at the same time described as having less back pain and better back motion. Most of the effects were still reported after 3 weeks. None of the horses were reported to show any sign of stress in the period between measurements.

Speeds

There were no statistical differences between the speeds selected for the horses. The averaged speed for all horses was 1.5±0.1 meters per second (m/s) at walk and 3.4±0.3 m/s at trot.

Stride parameters

There were no significant changes in stride duration or stride length at any gait (Tables 7.2 and 7.3).

Protraction-retraction angles

There were no changes in protraction and retraction angles at walk. At trot, maximal protraction and maximal retraction were reduced in the hindlimbs 1 hour after the treatment. Only in the left hindlimb this was still the case after 3 weeks. Also at trot, maximal protraction was reduced in the forelimbs 1 hour after the treatment, which was only in the right forelimb still present after 3 weeks (Tables 7.2 and 7.3).

Neck angle

There were no changes in the neck angle at any gait (Tables 7.2 and 7.3).

Limb kinematics

There were no changes in angular limb kinematics at walk and the changes were minimal at trot. The hip was 2.9 degrees more flexed during the swing phase 3 weeks after the treatment. The minimal vertical distance between the elbow and the hoof decreased 2.8 cm during the swing phase at trot indicating greater limb flexion.

Table 7.2. Range of motion (ROM) and angular motion pattern (AMP) values (mean ± SD, degrees) of vertebral and pelvic angles; mean ± SD of neck angle (degrees), stride length (meters) and stride duration (seconds); and protraction-retraction angles ROM, maximal protraction and maximal retraction (degrees) in horses with back pain before and after treatment with chiropractic manipulations at walk.

Motion			Before treatment	1 hour after treatment	3 weeks after treatment
Flexion-extension	T10	AMP	0.6±1.6	0.7±2.1	1.5±2.3
		ROM	6.0±1.5	6.3±1.9	6.0±1.2
	T13	AMP	-3.2±1.3*	-3.0±0.9*	-2.2±3.6*
		ROM	7.8±1.8	7.7±1.6	7.8±1.0
	T17	AMP	-3.1±1.2*	-2.9±1.1*	-0.5±2.2*
		ROM	8.0±1.6	7.8±1.4	7.9±1.0
	L1	AMP	-2.9±1.2	-2.5±1.3	-2.6±1.6
		ROM	7.8±1.4	7.8±1.1	7.8±1.2
	L3	AMP	-3.0±1.2*	-2.7±1.3*	-3.5±2.1
		ROM	7.7±1.4	7.4±1.2	7.3±1.3
	L5	AMP	-1.3±1.2*	-1.0±0.8*	-1.9±2.6
		ROM	6.4±1.1	6.4±1.5	6.2±0.9
Lateral bending	T10	AMP	3.9±4.8	2.7±4.8	2.5±3.5
		ROM	9.3±3.3	10.0±2.9	8.8±1.9
	T13	AMP	1.7±5.5	1.2±4.6	1.2±2.0
		ROM	5.3±0.9*	5.1±1.1	4.2±1.2*
	T17	AMP	1.4±5.3	-0.9±6.2	-0.8±3.3
		ROM	4.3±0.7*	4.0±1.3	3.3±0.6*
	L1	AMP	-0.9±5.5	-0.7±5.9	-0.6±5.1
		ROM	5.6±1.2	5.2±1.3	5.8±0.7
	L3	AMP	-1.7±6.5	-1.4±5.3	-1.3±5.2
		ROM	6.0±1.8	6.0±1.8	6.7±1.7
	L5	AMP	-0.9±7.4	-1.8±6.2	-1.5±6.3
		ROM	7.2±2.1	6.1±1.8	6.9±1.7
Pelvic inclination	Coxal tuberosity-hip	AMP	31.6±2.5	29.1±1.9	30.8±1.9
		ROM	8.5±3.5	6.7±5.4	6.9±5.4
Pelvic axial rotation	Sacral tuberosities	AMP	1.4±6.0*	0.6±3.5	0.1±4.7*
		ROM	18.2±4.2	18.0±2.4	17.0±3.1
Neck angle		AMP	84.6±2.0	83.1±1.0	83.5±1.5

Stride length		1.8±0.2	1.8±0.2	1.9±0.1
Stride duration		1.2±0.1	1.2±0.1	1.2±0.1
Protraction-retraction angles	Right hindlimb			
	max protraction	14.0	9.0	10.0
	max retraction	-22.1	-15.8	-16.7
	ROM	36.0±12.3	19.4±9.9	26.7±10.0
	Left hindlimb			
	max protraction	14.0	10.9	9.7
	max retraction	-21.3	-14.5	-17.2
	ROM	35.3±11.4	25.4±10.3	26.9±9.4
	Right forelimb			
	max protraction	12.5	7.6	7.6
	max retraction	-22.4	-18.5	-19.0
	ROM	34.9±10.1	26.1±13.3	26.5±12.4
	Left forelimb			
	max protraction	12.0	10.1	8.9
	max retraction	-22.7	-16.0	-17.5
	ROM	34.7±11.8	26.1±12.7	26.4±11.0

[*] Statistically significant differences between before and after first and/or second treatment.

Table 7.3. Range of motion (ROM) and angular motion pattern (AMP) values (mean ± SD, degrees) of vertebral and pelvic angles; mean ± SD of neck angle (degrees), stride length (meters) and stride duration (seconds); and protraction-retraction angles ROM, maximal protraction and maximal retraction (degrees) in horses with back pain before and after treatment with chiropractic manipulations at trot.

Motion			Before treatment	1 hour after treatment	3 weeks after treatment
Flexion-extension	T10	AMP	1.8±1.9	1.6±1.8	3.0±2.2
		ROM	4.2±1.4	3.9±1.2	3.6±0.9
	T13	AMP	-2.0±1.4*	-1.7±1.6	-0.1±4.0*
		ROM	2.8±0.5*	3.1±0.2*	2.5±0.7*
	T17	AMP	-2.0±0.8*	-1.7±0.2*	0.9±1.8*
		ROM	2.4±0.4*	3.1±0.3*	2.2±0.8*
	L1	AMP	-1.8±1.3	-1.7±1.1	-2.5±1.5
		ROM	3.0±0.5	3.6±1.5	3.1±0.7
	L3	AMP	-2.4±1.8*	-2.0±1.*	-3.8±1.5*
		ROM	4.0±1.5	3.9±1.6	4.2±0.6
	L5	AMP	-2.3±1.3*	-1.9±0.8 *	-3.5±2.0 *
		ROM	3.8±1.0	3.1±1.3	3.2±0.3
Lateral bending	T10	AMP	2.7±2.3	1.9±2.2	1.9±2.1
		ROM	5.8±2.0	6.3±2.0	6.5±2.9
	T13	AMP	1.9±5.2	1.6±3.7	1.7±2.9
		ROM	4.7±1.7	4.5±2.2	4.7±1.1
	T17	AMP	-1.9±4.2	0.3±1.6	0.4±1.7
		ROM	5.3±2.3	4.2±0.9	4.4±0.8
	L1	AMP	-0.9±3.2	-0.4±2.6	-0.7±3.9
		ROM	5.1±0.8	4.8±1.5	4.6±1.9
	L3	AMP	-0.9±4.5	-0.7±3.0	-0.7±2.9
		ROM	5.3±2.3*	5.8±2.3*	4.7±1.7
	L5	AMP	-2.1±6.0	-1.3±5.2	-1.5±6.0
		ROM	5.1±3.3	5.1±2.6	3.8±2.0
Pelvic inclination	Coxal tuberosity-hip	AMP	31.8±2.1*	30.2±1.2*	28.8±1.5*
		ROM	7.4±4.9	4.4±4.8	5.2±4.7
Pelvic axial rotation	Sacral tuberosities	AMP	1.6±3.1*	1.8±3.2	-0.3±3.4*
		ROM	22.6±3.5	18.5±2.3	17.8±4.0
Neck angle		AMP	80.8±1.4	83.6±0.9	81.1±0.9
Stride length			2.5±0.2	2.4±0.2	2.5±0.1

Stride duration		0.7±0.1	0.7±0.0	0.7±0.0
Protraction-retraction angles	Right hindlimb			
	max protraction	10.5*	4.6*	7.8
	max retraction	-18.7*	-13.4*	-15.3
	ROM	29.2±9.6	18.0±6.6	23.0±8.0
	Left hindlimb			
	max protraction	10.9*	4.9*	7.3*
	max retraction	-18.9*	-13.4*	-15.8*
	ROM	29.8±8.7	18.4±7.3	23.2±7.4
	Right forelimb			
	max protraction	8.3*	3.5*	3.6*
	max retraction	-21.4	-16.7	-20.0
	ROM	29.7±9.9	20.2±9.2	23.6±8.6
	Left forelimb			
	max protraction	8.8*	4.4*	6.3
	max retraction	-20.9	-15.8	-9.6
	ROM	29.7±6.6	20.2±8.8	23.4±7.9

* Statistically significant differences between before and after first and/or second treatment.

Vertebral Range of motion

There were no changes in flexion-extension (FE) ROM at walk. At trot the FE ROM was increased at T13 (0.3 degrees) and T17 (0.8 degrees) 1 hour after treatment and it was decreased after three weeks compared with before treatment (0.3 and 0.2 degrees, respectively). The other vertebral angles showed no significant changes in range of motion (Tables 7.2 and 7.3).

Lateral bending ROM was decreased in the angles at T3 and T17 after 3 weeks (1.1 and 1.0 degrees, respectively) at walk. At trot, lateral bending ROM was increased at L3 (0.5 degrees) at trot 1 hour after treatment, but there was no difference after 3 weeks compared to the situation before treatment (Tables 7.2 and 7.3).

No changes were seen in the range of motion axial rotation of the pelvis (Tables 7.2 and 7.3).

Vertebral angular motion patterns (AMPs)

All changes that were observed were present during the entire stride cycle and not only during certain phases of it.

The mean flexion-extension motion of some vertebral angles showed increased flexion at both gaits (Tables 7.2 and 7.3). At walk the segments at T13 and T17 were more flexed (by 0.2 degrees) during the first post-treatment measurement and by 1 and 2.4 degrees respectively during the last measurement. At trot, there was increased flexion at T17 (by 0.3 degrees) 1 hour after treatment; the flexion of the segments at T13 and T17 was, like at walk, increased 3 weeks after treatment by 1.9 and 2.9 degrees, respectively (Fig. 7.2). Also at trot, the segments at L3 and L5 were more flexed both by 0.4 degrees, during the first measurement after treatment, and more extended by 1.4 and 1.2 degrees respectively, during the second measurement after treatment. No changes were observed in the angle at L1 (Tables 7.2 and 7.3).

The mean lateral bending AMPs did not show significant changes at any gait; however the variability, showed in the SD, between horses was large (Tables 7.2 and 7.3).

The pelvic inclination was not affected at walk. At trot, the inclination of the pelvis was decreased 1.6 and 3 degrees 1 hour and 3 weeks after treatment, respectively (Tables 7.2 and 7.3).

There were no significant changes in the mean axial rotation of the pelvis 1 hour after treatment (Fig. 7.3). The AR AMP of the pelvis changed from 1.4 degrees before treatment to 0.1 degrees after 3 weeks at walk and from 1.6 degrees before treatment to -0.3 degrees after 3 weeks at trot, 0 being the mean of a perfectly symmetrical motion (Tables 7.2 and 7.3).

Discussion

All the patients included in this study had some degree of back pain and/or vertebral dysfunction as evidenced by the chiropractic examination. These cases were selected as cases representative of horses with back problems eligible for chiropractic treatment. In other words, the patient group can thus be seen as a good representation of the patient population for which it is claimed that chiropractic treatment can have beneficial effects. The treatment given was considered the most appropriate according to normal chiropractic practice. The treatment was exclusively applied by qualified veterinarians with formal training in equine chiropractic techniques. The chiropractic treatment aimed to restore normal joint motion, and at the improvement of altered neurological and tissue function.

In addition to clinically detectable back, neck or pelvic region pain, the horses in this study before the treatments showed reduced vertebral and pelvic motion compared with the motion of healthy horses described elsewhere (Johnston *et al.* 2004). These findings were similar to another study with horses with naturally occurring back pain, namely diminished flexion-extension range of motion of the thoracolumbar back and diminished axial rotation of the pelvis (Wennerstrand *et al.* 2004). It is known that induced back pain provokes stiffness in the thoracolumbar spine (Jeffcott *et al.* 1982) and this stiffness could become manifest as reduced ROM.

The present study was carried out using over-ground locomotion and not treadmill locomotion, which has been the method of choice in most studies concerning the equine back. It is acknowledged that the use of a treadmill would have reduced the variability in locomotion patterns and would have facilitated the capture of a greater number of strides, thus allowing for more accurate averaging procedures. However, it was the intention to carry out the present project under as much “real-life” clinical conditions as possible, including the selection of a patient population that was representative of the caseload at an equine veterinary chiropractic practice. This approach precluded the use of a treadmill because a reliable and repeatable locomotion pattern on a treadmill in horses not used to the device can only be obtained after various training sessions (Buchner *et al.* 1994) and any such intensive training programme was not feasible in this population of client-owned horses. There is an advantage in the use of over-ground locomotion as well, because horses could now be measured at their own preferred speed whereas on the treadmill they would have had to proceed at a predetermined speed because of the need for standardisation. In this study, the preferred speed of each horse was matched on each measurement because it is known that even minor changes in speed at the same gait may lead to subtle changes in back motion (Robert *et al.* 2001).

The effects of the chiropractic manipulations in this study were minor, but consistent. Range of motion tended to increase directly after treatment, but was decreased 3 weeks later compared with before the treatment; what may possibly have played a role here is the recurrence of back dysfunction. If the underlying cause of the problem was still present and left untreated, chiropractic treatment may just have had a temporary palliative effect. It is also possible that some of the horses would require several treatments at intervals to achieve a longer-term effect, while in this study horses received a single chiropractic treatment. The changes in angular motion patterns pointed at a more flexed back in the mid-thoracic area. This more flexed position had become more exaggerated after 3 weeks, both at walk and at trot. This increased flexion of the thoracic back contrasts with the more extended back observed in horses with induced back pain (Wennerstrand, unpublished results). The overall increased range of motion that was achieved is in agreement with other studies of manipulations in horses (Faber, *et al.* 2003; Haussler *et al.*1999) where it was concluded that manipulations improve segmental spinal motion.

Improvement of symmetry is one of the most important goals of chiropractic care. In this study, the treatment changed pelvic motion making it more symmetrical. This effect lasted at least 3 weeks. It goes without saying that a symmetrical pelvic rotation is one of the hallmarks of good gait and restoration of symmetry of pelvic motion will therefore be beneficial, but it should be realised that small asymmetries in pelvic motion may represent compensation for subtle lameness. If corrected for, the original lameness may become manifest and this may have happened in two of the horses in this study.

The treatment did not have clear effects on the angular motion patterns of the joints of the limbs. However, the protraction of the forelimbs and the retraction of the hindlimbs were reduced. These changes in protraction-retraction will increase back flexion according to the bow-and-string concept of the mammalian back as proposed by Slijper (1946). The changes in pro-retraction angles are interesting because, although it is known that severely and moderately lame horses modify their protraction-retraction patterns in order to unload the painful limb (Buchner *et al.* 1996b), changes in these angles are not distinctive of the locomotion pattern of horses with induced back pain (Jeffcott *et al.* 1982).

The subjective evaluations of the riders or owners were in most of the cases in agreement with the changes observed in the kinematic analyses. They observed decreased pain and improvement of motion (more symmetrical or increased back motion) when riding or exercising unridden still after 3 weeks. At the same time, some horses were noted “happier and moving easier”. These are, of course, highly subjective evaluations. It is generally assumed that there is a large placebo factor in the appreciation of the effects of treatments for back disorders by owners or riders and the reliability of the questionnaire outcome may be doubted. In fact, the longer stride length that was subjectively noted could not be substantiated by the kinematic analysis.

It can be concluded that the chiropractic manipulations had a subtle but statistically significant effect on several variables describing vertebral, pelvic and limb motion. These changes consisted of increased vertebral sagittal motion, increased pelvic rotational symmetry and an overall more flexed thoracic back with changes in protraction and retraction of the limbs. Given the increasing evidence of measurable effects on thoracolumbar and pelvic motion following chiropractic principles, the conclusion seems justified that veterinary equine chiropractic merits consideration as a valid therapy, alone or in conjunction with other methods, in the treatment of equine back problems. Investigations using larger cohorts of patients and having a longer follow-up than in this study are needed to assess the real clinical value of this therapeutic approach and to determine its place within the therapeutic options that are available to the equine practitioner to treat horses suffering from back pain.

Manufacturers’ addresses

[1] Qualisys Medical AB, Gothenburg, Sweden.
[2] Matlab® The MathWorks, Inc. Natick, MA.

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Chapter 8

General discussion

Introduction

This thesis aimed at augmenting the understanding of the relationship between motion patterns of the vertebral column and limbs by studying limb and/or spinal kinematics in horses subjected to a variety of interventions that are assumed to affect the motion balance between axial and appendicular skeleton. The interventions consisted of changing the position of the head and neck, inducing forelimb or hindlimb lameness, inducing back pain, and subjecting horses to chiropractic manipulations.

Experimental evidence supporting the bow-and-string principle

The bow-and–string concept of the mammalian back as originally proposed by Barthez (1798) and further elaborated and refined by Slijper (1946) states that a variety of actors outside the trunk itself influence back motion. These actors include forelimb and hindlimb pro- and retraction and also head and neck motion. In this concept, an upward movement of head and neck would induce extension of the back and downward motion would cause the opposite (Denoix and Pailloux 2001). Although intuitively plausible, this concept had never been proven experimentally in the horse. Experimental verification became urgent when the practice of training show jumpers and dressage horses with head and neck in hyperflexed position, also called “Rollkur” (Meyer 1992) or “Low, Deep and Round” (LDR) (Janssen 2003), became a topic of public discussion because of its alleged deleterious effects on the horse’s health.

Chapter 2 of this thesis shows that the head and neck indeed collaborate in the dynamical maintenance of the equilibrium of the body motion by provoking consistent changes in thoracolumbar kinematics: lowering the head flexes the bow while lifting the head extends the bow (Fig. 8.1). This experimental evidence fully supports the concept. A maybe less expected finding was that the head and neck also influence the flexion-extension (FE) range of motion (ROM) of the back. A low position increases FE ROM of the back while a high position reduces it considerably (Fig. 8.2). This is presumably due to the anatomical features of the thoracic back. Flexion of the back will separate the long thoracic spinous processes, while extension brings them together reducing the space between the processes, thus limiting ROM in a mechanical way. From the results of this study, it was concluded that the hyperflexed or LDR position in itself was not in anyway harmful to he horse; it even lent credibility to the position of some trainers that this way of training may help in optimising gymnastic performance of the horse. In fact, in the same study, where also an extremely extended head/neck position was investigated, it was shown that extreme high positions of the head and neck do have a big impact on limb timing and load distribution and can be considered to affect functionality much more than extremely low positions (Weishaupt *et al.* 2006). This study had important political consequences as it provided science-based data at an expert meeting on the subject of the *Fédération Equestre International* (FEI) in Lausanne in early 2006. At this meeting it was concluded that using this hyperflexed or LDR position in the training of horses could not be considered detrimental to the horse, provided that the technique is used by experienced horsemen/horsewomen for a limited time and in a proper way, and hence could not be banned (Jeffcott 2006).

The bow-and-string concept only considers motion in the sagittal plane, and describes the interaction of the head and limbs with the vertebral column in a two-dimensional way. This is a simplification of course, as real movement is 3-dimensional. Denoix and Pailloux (2001) have quantitatively described the 3D motion of the neck and its effect on lateral bending of the back modulated by the back muscles. In reality, the neck moves constantly outside the sagittal plane as there is a constant left-to-right motion generated by simultaneous lateral bending and axial rotation. This coupled motion of the neck leads to thoracolumbar lateral bending, and, as shown in **Chapters 5** and **6**, this thoracolumbar lateral bending also affects limb motion, as limb position follows changes in configuration of the spine. The pelvis is another important element that is not considered in the bow-and-string model. In this thesis, the axial rotation and the inclination of the pelvis have been taken into account. However, further studies are needed that focus on the quantitative and detailed description of the relationship between the pelvis, the hindlimbs and the vertebral column and may ultimately result in an improvement and refining of the classical bow-and-string concept.

Lameness and spinal motion

Coexisting back pain and lameness is not uncommon (Marks, 1999). However, finding the primary cause of the problem is difficult. One of the main findings in this thesis was that even a very subtle lameness provokes consistent and statistically significant changes in thoracolumbar kinematics. This observation emphasises the effect of changes in limb loading on spinal kinematics and confirms the widespread clinical impression that lameness is a frequent pathogenetic factor in back pain (Dyson 2005; Landman *et al.* 2004). Thus, back pain is likely to be secondary in many cases.

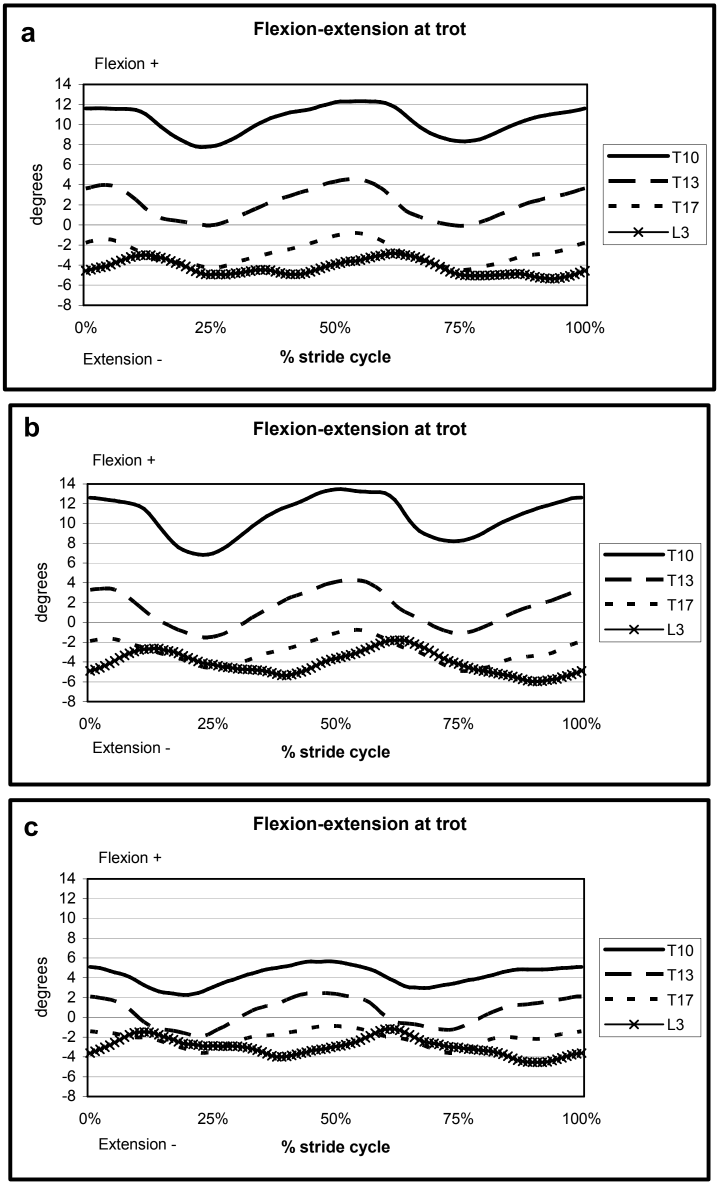

Fig.8.1 Example of flexion-extension patterns of four measured vertebral angles of one horse at trot with a) free position of the head and neck, b) extreme low and rolled-up and, c) extreme high position of head and neck.

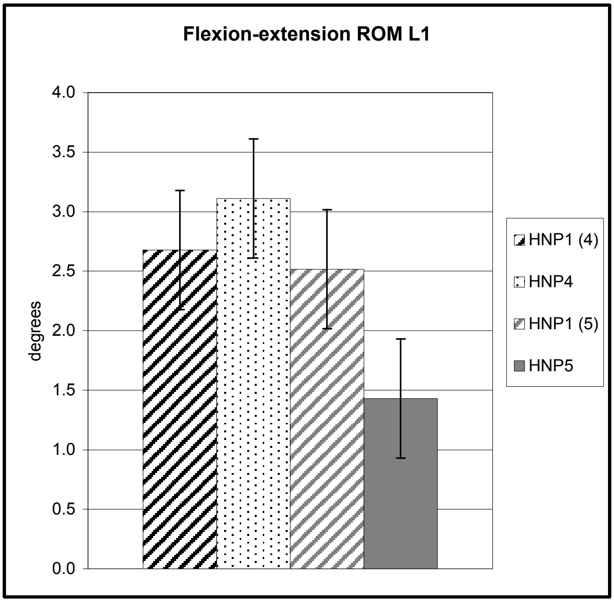

Figure 8.2. Flexion-extension range of motion of the angle at L1 (T17-L1-L3) with two different head and neck positions (HNP): HNP1 (4) free position at same speed as HNP4, HNP4: hyperflexed position (low and rolled-up), HNP1 (5): free position at same speed as HNP5, HNP5: extremely high position of head and neck

Both forelimb (**Chapter 3**) and hindlimb (**Chapter 4**) lameness will affect the motion chain limb-back-head. In both cases the horse will attempt to unload the painful limb, which load redistribution will affect back motion through different mechanisms for fore and hind limb. It is known that severe or moderate lameness affects, besides head motion, linear and temporal stride parameters and limb pro- and retraction angles of the limbs. It is interesting that slight lameness does not affect any of the limb-related parameters, but still has a consistent and significant effect on the axial skeleton and pelvis. In fact, spinal motion patterns can be seen as more sensitive indicators of slight lameness than limb motion. Slight forelimb lameness has a direct effect on the thoracolumbar back: at trot there is an increased flexion at the withers accompanied by lowering of the head during the stance phase of the sound diagonal, increased extension of the thoracolumbar back during the stance phase of the lame diagonal, and increased lateral bending towards the lame side during the lame diagonal. A slight hindlimb lameness has a direct effect on pelvic motion, it induces axial rotation towards the non-lame side, and also provokes lowering of head and neck together with increased flexion at the withers during the lame stance phase.

Biomechanical impact of back pain

The findings in **Chapters 5** and **6** confirmed and reinforced the conclusions from the preceding two chapters. Here it was shown that induced back pain affects back kinematics in a rather substantial way, which was expected, but provokes only very subtle changes in the biomechanics of the limbs, most of which are only detectable during the swing phase and thus do not affect limb loading. Here it becomes clear that primary back pain only minimally affects the motion pattern of the limbs, in contrast to what happens with back motion in the reverse situation when the primary ailment is located in the limbs. It is thus much less probable to find lameness secondary to back pain than back pain secondary to lameness. This statement is of relevance for equine practice because it stresses that prevention and treatment of lameness are likely to have a direct influence on the prevention and treatment of back problems.

The main kinematical signs of back pain are changes in range of motion, a more extended posture of the vertebral column, together with muscle stiffness and decreased limb flexion during swing. In more equestrian terms this could be summarised as a less animated gait. This will often be interpreted as poor performance, which is a frequently reported sign of back problems.

The changes in vertebral motion patterns seem to depend upon both the anatomical location of the painful site and on the evolution of pain over time. In this thesis, back pain was induced unilaterally. This is different to most clinical back patients where bilateral pain is a much more common finding than strictly unilateral pain. In most cases of back pain in patients total range of motion of the back is decreased (Wennerstrand *et al.* 2004). The unilateral back pain model used in this thesis led to an increase in motion, probably caused by the loss of the normal balance between the left and right epaxial musculature. Furthermore, in the experiment muscle stiffness assessed by palpation was accompanied by an increased range of spinal motion. In fact, when referring to the back, the clinical term stiffness might be misleading. Stiffness of back muscles does not necessarily mean “stiffness of the back”, which can lead to reduced back motion.

It was interesting to note in the horses with induced back pain that more kinematical changes could be seen after a few days than in the first 24 hours. This may reflect the difference between back pain and muscle stiffness that follows after some days from which it may be speculated that muscle stiffness provokes more changes than acute muscle pain, or that horses can cope easier with pain than with lack of muscle function due to stiffness.

Kinematical assessment of treatment for back pain

Present-day equine gait analysis technology allows for the accurate and detailed analysis of both limb and back kinematics. Kinematical analysis is a useful tool, therefore, to assess the effects of any treatment aiming at the improvement of locomotion and/or back function.

In **Chapter 7** the effect of treating back pain in the horse with chiropractic manipulations was studied. Any treatment that eliminates back pain would induce biomechanical changes in the vertebral column. However, a quantifiable change in motion does not necessarily mean that the pain and/or the cause of pain have been completely eliminated. As mentioned earlier, pain can be assessed in horses by observing behavioural signs (Ashley *et al.* 2005) and/or by the use of special devices such as an algometer that determines the mechanical nociceptor threshold in the axial skeleton (Haussler and Erb 2006a, b). For an adequate assessment of the effectiveness of a therapy, a combination of detailed kinematical and/or kinetic analysis, quantitative pain assessment and clinical examination would be most appropriate.

The way forward

Kinematical analysis has proven to be an excellent tool to assess motion patterns of both the equine vertebral column and limbs. The technique allows for the accurate quantification of angular and positional data, thereby quantifying changes in kinematics that are too subtle to be assessed by clinical examination, or that occur in parts of the body that are either moving very fast (*e.g.* the distal limbs), or at a site where the angle of inspection during a clinical examination is far from optimal, such as in case of the back. The work in this thesis has shown that by using the kinematic approach it is possible indeed to improve the understanding of the complex motion chains that connect the axial and appendicular skeleton in the horse. In some cases, kinetic data could be generated as well with a novel method that calculates ground reaction forces from kinematic data (Bobbert *et al.* 2007). However, the availability and clinical applicability of these techniques are limited. At present, kinematic and/or kinetic analysis in the horse requires expensive equipment, experienced personnel, ample time to analyse data, a standardized technique and previous treadmill training, which owners are not always willing to accept, together with some other disadvantages. Thus far, the visual clinical examination, realized by an experience veterinarian has been the standard in clinical practice. It has the advantage that the human eye is excellent in pattern recognition and the clinician will thus assess whole body mechanics in real time. This procedure can be quite accurate if enough experience is present, but he/she can not give a quantitative assessment of the problem or detect the very subtle biomechanical changes alluded to above. Hopefully, the combination of both, clinical experience and accurate quantification via computerized gait analysis systems will be the clinical scenario in the near future. To achieve this, current technologies urgently require modifications aiming at increased practicality, efficiency and cost-reduction. Improvement of hardware and equine motion analysis software should progress together with equine sport medicine, which actually is most of the time not the case in equine biomechanics research.

This thesis has contributed to a better understanding of the complex mechanisms and interactions that underlie equine back function. The equine back has always been seen as an enigmatic structure. It is anticipated that with the advent of easy-to-use measuring techniques studies can be performed more easily, eventually leading to a comprehensive knowledge of and insight in function and dysfunction of the equine back.

General conclusions

- The position of head and neck is an important determinant of vertebral motion. High positions restrict normal back motion more than low positions when comparing with free (normal) positions.

- The motion of the appendicular skeleton influences the axial skeleton motion more than the other way around.

- Subtle forelimb and hindlimb lameness affect vertebral and pelvic motion in a consistent way.

- Moderate back pain has a considerable impact on vertebral motion, but affects limbs kinematics only slightly.

- The main kinematical signs of back pain are changes in the range of motion, extension of the vertebral column and decreased limb flexion during the swing phase or dragging of the limbs.

- The signs of back pain depend on the anatomical location and evolution of the problem.

- Treatment of back pain affects full body kinematics of locomotion.

The equine community should be aware of the implications of the tight functional relationship between vertebral column and limbs. When pain is present in any component, the balance between them will be affected. In a similar way, when changes in posture are imposed to the horse the whole motion chain within the axial and appendicular skeleton will be influenced.

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Summary in English

Nowadays, sport horses have to train and perform in high-level sportive and intense leisure activities that put increased demands on their limbs and vertebral column. Therefore, injuries of the locomotor system accompanied by decreased functionality and pain in neck and back area are often seen in these horses when they are presented to equine hospitals with a history of “poor performance”.

The relationship, however, between limbs and vertebral column function still is poorly understood and has been of scientific interest for long time in the equine and in other species. To date, the bow-and–string concept of the mammalian back (Chapter 1) has been the common, age-old thought on this matter and implies in simple terms that several body parts influence back motion in the sagittal plane (Barthez 1798; Slijper 1946).

Focussing on the equine, the origin and pathogenesis of back dysfunction are difficult to predict with clinical examination alone, and thus deserve an objective evaluation and investigation. Modern gait analysis technology allows for such an objective, more accurate and detailed analysis of body kinematics to study in three-dimensions how limbs interact with vertebral column movement and vice versa.

Thus, the purpose of this thesis was to improve the understanding of the biomechanical relationship between motion patterns of the axial and appendicular skeleton of the horse. Body kinematics of different groups of horses were investigated by experimentally exposing them to different head and neck positions, to induced, but reversible lameness and back pain, or to chiropractic treatments. All of which might influence the balance in motion chains that lie at the basis of the concerted action of limbs and back in the horse.

In Chapter 2 six different head and neck positions were studied, some of them commonly used for dressage training and some in competition. The results showed that head and neck positions affected only the flexion-extension motion of the vertebral column in the sagittal plane, which is in accordance with the bow-and–string concept. By keeping the head and neck in a lower position the back became more flexed and showed an increased range of motion (ROM). By keeping the head and neck in an higher position the back became more extended and was its ROM reduced. Additionally, in an extremely high position of the head and neck the vertebral motion pattern became less symmetrical and hindlimb protraction was reduced. Thus, it was concluded that changes in head and neck position will directly induce changes in back kinematics. Low positions would increase vertebral movement and extremely high positions would reduce it. In this way, this study provided quantitative data on the effect of head and neck positions on thoracolumbar motion and may help in discussions on the ethical acceptability of some modern training methods.

Back pain and lameness do coexist, but in the clinical situation the primary cause of the problem is apparently more commonly found in the limbs. The experimental investigation of this statement and the detailed description of the pathogenesis of back pain and lameness have not been studied until now. In Chapter 3 and 4 the relation between a slight lameness and vertebral motion was investigated by inducing a reversible lameness. It was shown that even subtle forelimb and hindlimb lameness provoked systematic changes in pelvic and thoracolumbar kinematics. After forelimb lameness had been induced, the vertebral ROM increased and the pattern of thoracolumbar motion in the sagittal and horizontal planes changed. Hindlimb lameness resulted in hyperextension and increased ROM of the thoracic back, but also in a decreased ROM of the lumbosacral segment. All changes presumably are done in an attempt to unload the affected limb. It may be surmised that, when chronically present, subtle lameness could induce back dysfunction.

In Chapters 5 and 6 the effect of induced unilateral back pain on vertebral and limb motion was studied. The results showed that back pain affects both back as well as limb kinematics. Vertebral ROM became increased, the position of the back was more extended and showed increased lateral bending. On the other hand, the effect of back pain on limbs was rather minimal consisting of decreased flexion of some of the joints of all four limbs during swing phase. Thus, it can be concluded that primary back pain is unlikely to produce important changes in the limbs.

In Chapter 7 the effect of chiropractic manipulations on horses with back pain was studied. Understanding the effect of back and limb pain experimentally, it could be hypothesized that treating back pain would induce biomechanical changes in the vertebral column and in a smaller amount in the limbs. Chiropractic manipulations provoked slight but significant changes in thoracolumbar and pelvic kinematics. The changes in the limbs were minimal. The main effect of the chiropractic manipulations was a less extended thoracic back, enhanced vertebral ROM, reduced inclination of the pelvis and improved pelvic motion symmetry.

In summary, from the results of this thesis the following statements can be made: the position of head and neck is an important determinant of vertebral motion; subtle lameness affect vertebral and pelvic motion in a consistent way while back pain affects limbs kinematics only slightly; the main kinematical signs of back pain are changes in the range of motion, extension of the vertebral column and decreased limb flexion during the swing phase; and finally that treatment of back pain affects full body kinematics of locomotion.

It can be concluded that motion of head, vertebral column and limbs strongly influence each other and pain on any of these structures affects the balance between them.

Nederlandse Samenvatting

De sportpaarden moeten tegenwoordig trainen en presteren op het hoogste niveau, wat een toenemende belasting betekent voor benen en wervelkolom. Daarom wordt bij paarden die aangeboden worden aan paardenklinieken met de klacht “poor performance”, steeds vaker letsel aan het bewegingsapparaat gezien in combinatie met een afgenomen functionaliteit en pijn in de nek en rugsegmenten.

De functionele relatie tussen de beweging van de benen en die van de wervelkolom is slechts ten dele begrepen en is al lang onderdeel van vele wetenschappelijke studies bij zowel paarden als bij andere diersoorten.

Tegenwoordig is het zogenaamde bow-and–string principe (Hoofdstuk 1) nog steeds een algemeen geaccepteerd begrip, hetgeen inhoudt dat de verschillende onderdelen van het muskuloskeletale systeem invloed uitoefenen op de beweging van de rug in het sagittale vlak (Barthez 1798; Slijper 1946).

Toegespitst op het paard zijn het ontstaan en de pathogenese van een disfunctionerende rug moeilijk te destilleren uit alleen het klinisch onderzoek, en dus verdient een objectief onderzoek de voorkeur. Moderne bewegingsanalyse technieken maken een dergelijke objectieve, meer preciese en gedetailleerde 3-dimensionale analyse van de kinematica van de benen in samenwerking met de rug mogelijk.

Het doel van dit proefschrift was om de kennis uit te breiden naar de biomechanische verhoudingen tussen de bewegingspatronen van wervelkolom en de ledematen van het paard. De kinematica van diverse groepen paarden zijn onderzocht door hen bloot te stellen aan verschillende hoofd/hals houdingen, geïnduceerde, edoch reversibele kreupelheden en rugpijn, en aan een behandeling d.m.v. chiropractie. Deze factoren zouden namelijk de balans verstoren tussen de bewegingssegmenten die aan de basis liggen van de georchestreerde actie van benen en rug bij het paard.

In Hoofstuk 2 zijn zes verschillenden hoofd/hals posities bestudeerd, waarvan sommige alleen toegepast worden in huidige trainingsmethodieken voor de dressuur en anderen ook in de wedstrijden. De resultaten laten zien dat de hoofd/hals positie slechts het buigen en het strekken van de wervelkolom in het sagittale vlak beïnvloedt, hetgeen in overeenstemming is met het eerdere genoemde bow-and–string principe. Als hoofd en hals in een lagere positie gehouden worden, wordt de rug meer gebogen en vertoont deze een toegenomen bewegingsuitslag. Door hoofd en hals in een hogere positie te houden wordt de rug in een meer gestrekte positie gehouden en wordt de bewegingsvrijheid verminderd. Bovendien wordt bij een extreem hoge hoofd/hals positie de beweging van de wervelkolom minder symmetrisch en wordt de bewegingsuitslag van de achterbenen verminderd. Daarom kon geconcludeerd worden dat veranderingen in de hoofd/hals positie direct veranderingen induceren in de kinematica van de rug. Lage positie laten de beweging van de wervelkolom toenemen en extreem hoge houding laten deze afnemen. Op deze manier gaf deze studie kwantitatieve resultaten op het gebied van het effect van hoofd/hals houdingen op de bewegingen van de rug in het thoracolumbale gebied en kon zo een bijdrage leveren aan de discussie over het ethisch accepteren van sommige van deze moderne training methoden.

Rugpijn en kreupelheid hangen met elkaar samen, echter in een klinische setting is de hoofdoorzaak van een disfunctionerende rug meestal in de benen te vinden. Experimenteel onderzoek naar deze relatie en een gedetailleerde beschrijving van pathogenese van rugpijn en kreupelheid zijn tot nu nog niet echt goed bestudeerd. In Hoofdstuk 3 en 4 is de relatie tussen kreupelheid en beweging van de wervelkolom onderzocht door een reversibele kreupelheid op te wekken. Daarbij is aangetoond dat een subtiele voorbeens- en achterbeenskreupelheid resulteerde in systematische veranderingen in de beweging van het thoracolumbale deel van de rug en het bekken. Nadat een voorbeenskreupelheid was opgewekt, nam de bewegingsuitslag van de wervelkolom toe en is het bewegingspatroon thoracolumbaal in het sagittale en horizontal vlak veranderd. Een achterbeenskreupelheid resulteerde in het meer strekken en een toename in de bewegingsuitslag van het thoracale gedeelte van de rug, maar een afgenomen bewegingsuitslag van het lumbosacrale segment. Alle veranderingen komen waarschijnlijk voort uit een poging van het paard het aangedane been te ontlasten. Het mag worden aangenomen dat, indien chronisch, een subtiele kreupelheid een meer permanent disfunctioneren van de rug induceert.

In Hoofdstuk 5 en 6 is het effect van een geïnduceerde unilaterale rugpijn op wervelkolom en beweging van het been bestudeerd. De resultaten laten zien dat rugpijn zowel de kinematica van de rug als die van de benen beïnvloedt. De bewegingsuitslag van de wervelkolom is toegenomen, terwijl de positie van de rug meer gestrekt werd en een toegenomen laterale buiging liet zien. Tegelijkerijd was het effect van pijn in de rug op de benen minimaal en bestond uit een afgenomen buiging van enkele gewrichten. Als zodanig, kan worden geconcludeerd dat primaire rugpijn resulteert in geringe, secundaire veranderingen in de beweging van de benen.

In Hoofdstuk 7 is het effect van chiropractie op paarden met rugpijn bestudeerd. Uitgaande van de kennis over de biomechanische effecten van een experimentele rug- en beenpijn, zouden bij de behandeling van rugpijn veranderingen moeten optreden in zowel de beweging van de wervelkolom en als in gelijke mate in de benen. Na chiropractische manipulatie zagen we significante veranderingen in thoracolumbale and bekken kinematica. De veranderingen in de bewegingen van het been waren echter minimaal. De belangrijkste effecten van een chiropractische manipulatie waren een minder gestrekte rug in het thoracale gebied, een grotere bewegingsuitslag van de wervelkolom, een afgenomen helling van het bekken en een toegenomen symmetrische beweging van het bekken.

Uit de resultaten van dit proefschrift kunnen de volgende conclusies worden getrokken: de hoofd/hals houding is een belangrijke determinant in de beweging van de wervelkolom: een subtiele kreupelheid heeft invloed op de beweging van wervelkolom en bekken op een consistente manier, rugpijn beïnvloedt de kinematica van de ledematen slechts minimaal, de belangrijkste kinematische veranderingen veroorzaakt door rugpijn zijn veranderingen in de bewegingsuitslag en het meer strekken van de wervelkolom en een afgenomen buiging van de benen gedurende de zwaaifase, en tenslotte heeft een chiropractische behandeling van rugpijn invloed op de kinematica van het gehele lichaam, dat wil zeggen op de rug en benen.

Samenvattend kan worden gesteld dat de beweging van hoofd, wervelkolom en ledematen elkaar duidelijk beïnvloeden en pijn de balans tussen deze segmenten duidelijk verstoord.

Resumen en Castellano

Hoy en día, los caballos de deporte deben entrenar y ejecutar actividades deportivas de alto nivel e intensas actividades recreativas de gran exigencia para las extremidades y la columna vertebral. Por este motivo, lesiones del sistema locomotor acompañadas de funcionalidad disminuida y dolor en la columna vertebral son observados frecuentemente en pacientes referidos a hospitales equinos con una historia de rendimiento deportivo pobre.

Sin embargo, la relación entre las extremidades y la columna vertebral es aún poco entendida y ha sido de interés científico por largo tiempo en el equino y en otras especies. Hasta la fecha, el concepto del “arco y cuerda” del dorso del mamífero (Capítulo 1) ha sido el pensamiento común, aunque antiguo, sobre esta materia e implica en términos sencillos que diferentes partes del cuerpo influyen en el movimiento de la columna toracolumbar en el plano medio (Barthez 1798; Slijper 1946).

Enfocándose en el equino, el origen y la patogénesis de la disfunción de la columna vertebral son difíciles de predecir sólo con el examen clínico, por lo tanto merece una evaluación e investigación objetiva. Los sistemas modernos de análisis de la marcha permiten realizar tal preciso, detallado y objetivo análisis de la cinemática corporal con el fin de estudiar en tres dimensiones cómo las extremidades interactúan con el movimiento de la columna vertebral y viceversa.

Por consiguiente, el propósito de la presente tesis fue aportar al entendimiento de la relación biomecánica entre los patrones de movimiento del esqueleto axial y apendicular del caballo. La cinemática corporal de diferentes grupos de caballos fue investigada exponiéndolos experimentalmente a diferentes posiciones de la cabeza y el cuello, a cojera inducida, a dolor inducido de dorso, y a tratamientos quiroprácticos. Todo lo cual puede influenciar el equilibrio de los movimientos en cadena que yacen en la base de la acción conjunta de las extremidades y la columna del equino.

En el Capítulo 2, fueron estudiadas seis posiciones diferentes de la cabeza y cuello. Algunas de ellas, comúnmente usadas en entrenamiento y competiciones de doma clásica. Los resultados mostraron que la posición de la cabeza y cuello afectan el movimiento de flexión y extensión de la columna en el plano medio, lo cual concuerda con el concepto del “arco y cuerda”. Manteniendo la cabeza y cuello en una posición baja, la columna vertebral adquiere una mayor flexión e incrementa su rango de movimiento (RDM) en el mismo plano. Manteniendo la cabeza y cuello en una posición alta, la columna adquiere una mayor extensión y reducción de su RDM. Adicionalmente, en una posición de la cabeza y cuello extremadamente alta, el patrón de movimiento vertebral se tornó menos simétrico y la protracción de las extremidades posteriores se redujo. Por consiguiente, pudo concluirse que cambios en la posición de la cabeza y cuello induce en forma directa cambios en la cinemática vertebral. Posiciones bajas aumentarían el movimiento vertebral y posiciones extremadamente altas lo reducirían. De esta manera, el presente estudio provee datos cuantitativos sobre el efecto de diferentes posiciones de la cabeza y cuello, y permite contribuir a las discusiones sobre la aceptabilidad ética de algunos métodos modernos de entrenamiento.

El dolor de dorso y cojera coexisten. En el marco clínico la causa primaria de este problema es al parecer más comúnmente encontrada en las extremidades. La investigación experimental de esta afirmación y la descripción detallada de la patogenia del dolor de dorso y cojera no habían sido investigadas hasta la fecha. En el Capítulo 3 y 4, fue estudiada la relación entre cojera leve y el movimiento de la columna a través de la inducción de cojera reversible. Los resultados mostraron que incluso una cojera leve del miembro anterior y posterior provoca cambios sistemáticos en el movimiento toracolumbar y pélvico. Durante la inducción de cojera del miembro anterior, el rango de movimiento vertebral aumentó y el patrón de movimiento toracolumbar en el plano medio y horizontal se vio modificado. En el caso de la cojera del miembro posterior, ésta resultó en hiperextensión e incremento del RDM de la columna torácica, pero también en reducción del RDM del segmento lumbosacral. Presumiblemente, todos estos cambios son realizados con el objetivo de reducir la fuerza ejercida sobre el miembro afectado. Es posible presumir que si una cojera leve se presenta en forma crónica, ésta podría provocar una disfunción en la columna.

En los Capítulos 5 y 6, fue estudiado el efecto del dolor inducido en el dorso sobre cinemática vertebral y de las extremidades. Los resultados mostraron que el dolor de dorso afecta tanto el movimiento de la columna como de las extremidades. El rango de movimiento vertebral fue incrementado, la posición de la columna se volvió más extendida y presentó un aumento en lateroflexión. En contraste, el efecto del dolor de dorso sobre las extremidades fue mínimo consistiendo en una disminución en el grado de flexión de algunas de las articulaciones de todas las extremidades durante la fase de vuelo. Por consiguiente, fue posible concluir que es improbable que el dolor primario del dorso produzca importantes cambios en las extremidades.

En el Capítulo 7, fue estudiado el efecto de manipulaciones quiroprácticas en caballos con dolor de dorso. Entendiendo el efecto del dolor de dorso y de las extremidades (cojera) en forma experimental, es posible establecer la hipótesis de que el tratamiento del dolor de dorso induciría cambios biomecánicos en la columna vertebral y, en menor proporción, en las extremidades. Los resultados mostraron que las manipulaciones quiroprácticas provocaron cambios leves pero significantes en la cinemática toracolumbar y pélvica. Los cambios en la cinemática de las extremidades fueron mínimos. El principal efecto del tratamiento fue menor extensión de la columna torácica, aumento del rango de movimiento vertebral, reducción del ángulo de inclinación de la pelvis y mejoría de la simetría del movimiento axial pélvico.

En resumen, las siguientes afirmaciones pueden ser establecidas: la posición de la cabeza y cuello es un importante determinante de la cinética vertebral; una cojera leve afecta el movimiento vertebral y pélvico en forma consistente, en cambio, un dolor de dorso afecta el movimiento de las extremidades sólo en forma mínima; los principales signos cinemáticos de dolor de dorso son cambios en el rango de movimiento vertebral, extensión de la columna y flexión disminuida de las extremidades durante la fase de vuelo; y finalmente, el tratamiento de problemas del dorso afecta la cinemática de la locomoción en el equino.

Es posible concluir que los movimientos de la cabeza, de la columna vertebral y de las extremidades afectan enormemente el uno al otro y que la presencia de dolor en cualquiera de estas estructuras afecta su equilibrio mutuo.

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Curriculum Vitae

English
Constanza B. Gómez Álvarez was born on April 8th 1976 in Santiago de Chile. She went to high school in the city of Temuco and started her education in Veterinary Medicine in the Universidad Católica de Temuco in 1994. She graduated as a Doctor in Veterinary Medicine and “Licenciada” in Veterinary Sciences with distinction in 1999. She was hired at the same university as Assistant Instructor in Animal Physiology and Veterinary Anatomy Department where she taught during four years. In 2003 she moved to The Netherlands to begin her PhD under the supervision of Prof. dr. P. René van Weeren of the Department of Equine Sciences. The result of her research is presented in this book.

Nederlands
Constanza B. Gómez Álvarez werd geboren op 8 April 1976 te Santiago de Chili. Zij ging naar de middelbare school in de stad Temuco en begon daar in 1994 de studie diergeneeskunde aan Universidad Católica. In 1999 behaalde zij haar diploma en “Licenciada” met onderscheid in Veterinaire Wetenschappen. Zij werd aangesteld aan dezelfde universiteit als junior docent in Dieren Fysiologie bij de Veterinaire Anatomie afdeling waar zij gedurende vier jaar onderwijs gaf. In 2003 verhuisde Constanza naar Nederland voor haar promotie onderzoek, onder de supervisie van Prof. dr P. René van Weeren van het departement Gezondheidszorg Paard. Het resultaat van dit onderzoek wordt gepresenteerd in dit boek.

Castellano
Constanza B. Gómez Álvarez nació el 8 de Abril de 1976 en Santiago de Chile. Realizó su educación media en la ciudad de Temuco y en 1994 comenzó su educación universitaria en la carrera de Medicina Veterinaria en la Universidad Católica de Temuco. Se graduó de Médico Veterinario y Licenciada en Medicina Veterinaria con distinción en 1999. Fue contratada en la misma universidad como profesor instructor en el Departamento de Fisiología Animal y Anatomía Veterinaria donde enseñó durante cuatro años. En el año 2003, Constanza viajó a Los Países

Bajos para comenzar su doctorado bajo la supervisión del Profesor dr. P. René van Weeren del Departamento de Ciencias Equinas. El resultado de su trabajo de investigación se presenta en este libro.