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Gait analysis of forelimbs in Thoroughbreds with
metacarpophalangeal joint injuries

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GAIT ANALYSIS OF FORELIMBS IN THOROUGHBREDS WITH METACARPOPHALANGEAL JOINT INJURIES

By

Patricia Eliza de Almeida

A THESIS

Submitted to
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ABSTRACT

GAIT ANALYSIS OF FORELIMBS IN THOROUGHBREDS WITH METACARPOPHALANGEAL JOINT INJURIES

BY

Patricia Eliza de Almeida

This study aimed to determine biomechanical variables for the diagnosis of lameness, and to use graphical representations of data to enhance the understanding of the movement pattern in horses with fetlock joint lameness. Five lame (group 1) and five sound (group 2) horses had kinematic and ground reaction forces (GRF) data recorded at trot. Group analysis demonstrated that the lame limb had significantly smaller ($p<0.05$) fetlock joint maximum extension angle and vertical GRF peak (220°; 7.9N/kg) than the sound limb (239°; 10.8N/kg). Lame horses also showed longer ($p<0.05$) stance duration (49%) than sound horses (43%). Due to high variability between horses, single-subject analysis was used to detect intra-individual differences between forelimbs of group 1 (e.g. horse 2 peak braking GRF: lame = -1.4N/kg, contralateral = -0.6N/kg; $p<0.05$). Graphical displays including kinegrams and force vector diagrams facilitated identification of the lame limb versus the contralateral limb. Variability of some kinematic and GRF measures was reduced in the lame horses, which may be caused by compensatory mechanisms to reduce pain in the affected limb. Biomechanical measures, including movement variability, may assist clinicians in objectively assessing lameness, improving the understanding of gait abnormalities and evaluating improvement in response to therapy.

DEDICATION

In loving memory of my grandmother Eulalia.

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- My family for unconditional support and love.
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CHAPTER 1

INTRODUCTION

Orthopedic injuries in racing Thoroughbred horses often involve severe trauma to bones and soft tissues of the limb. These injuries have a severe, sudden, and dramatic onset, and their presence limits future performances (Cohen *et al.*, 1997). In Thoroughbreds, 90% of musculoskeletal racing injuries involve the forelimbs, and these injuries are primarily located in the carpal joint, metacarpophalangeal joint and metacarpal bone. Most of the catastrophic racing injuries, however, involve the suspensory apparatus of the forelimbs (Peloso *et al.*, 1994). In young horses, the suspensory ligament is the weakest link in the suspensory apparatus. Active training appears to strengthen the suspensory ligament, so in racing horses the weakest component of the apparatus becomes the proximal sesamoid bones (Bukowiecki *et al.*, 1987). Moreover, during exercise, fatigue of the soft tissues that support the distal limb may allow excessive extension of the metacarpophalangeal joint, when tensile forces may exceed the biomechanical tolerance of the structures, leading to failure of the bone or soft tissues (Hubert *et al.*, 2001).

Following an orthopedic injury, the main clinical sign is lameness. Lameness is defined as a clinical manifestation of abnormal gait, and it is indicative of a structural or functional disorder in one or more limbs, or in the back (Wittmann, 1931; West, 1984; Stashak, 1987; Wyn-Jones, 1988; Speirs, 1994; Wilson & Keegan, 1995). Under clinical conditions, the diagnosis of lameness is based on experience and ability of the clinician to detect asymmetries and abnormalities in the locomotion pattern. During the lameness evaluation, the equine clinician assesses the severity of lameness and assigns a grade based on a standard scoring system (Swanson, 1984) from 1 (least severe) to 5 (most severe). This grading system offers subjective information about the severity of lameness, but its use has been found to be unreliable because of a lack of agreement between clinicians with different levels of expertise when scoring a mild lameness (Keegan *et al.*, 1998). Further, the grading score system poorly correlates with objective measures of locomotion, such as ground reaction forces (Fuller *et al.*, 2002).

The biomechanical changes associated with lameness lead to alterations in the limb loading profile, and in the force distribution within and between the limbs (Goodship *et al.*, 1983; Morris & Seeherman, 1987; Merkens *et al.*, 1988). For instance, lame horses show a progressive reduction of the vertical and longitudinal braking components of the ground reaction forces (GRF). Asymmetry of GRFs between lame and sound limbs has been shown at walk (Merkens & Schamhardt, 1988) and trot (Morris & Seeherman, 1987; Clayton *et al.*, 2000). The peak vertical force (F_z) of the lame limb has been found to be 11.5% to 27% less than that of the sound limb, depending on the severity of lameness (Morris & Seeherman, 1987; Clayton *et al.,* 2000). In addition, changes in limb kinematics, such as joint angular patterns, can also indicate local pain or mechanical disturbances associated with lameness (Stashak, 1996). For example, a significant ($p<0.05$) reduction of approximately 6° in maximum metacarpophalangeal (fetlock) joint extension angle, and significant reduction of approximately 3.8° in maximum coffin joint flexion angle have been reported during experimentally induced forelimb lameness (Buchner *et al.*, 1996). An important feature of biomechanics is the movement variability, found to be intrinsic in all movement patterns (Bernstein, 1967). The wide variety of orthopedic diseases is likely to increase the biomechanical variability between horses, which is supported by disease-specific changes found in GRFs between horses (Williams *et al.,* 1999). In addition to inter-individual variation, a decrease in intra-individual variability appears to play an important role as a mechanism to diminish pain in horses (orthopedic disease) (Peham *et al.*, 2001).

Specialized diagnostic techniques that are able to detect these biomechanical changes provide a more sensitive quantitative assessment of lameness severity but, so far, they have not been widely used to assist in detection of lameness. Such techniques, as well as improving lameness diagnostics, could be used to monitor progress and assess the success of therapy (Keg *et al.*, 1994; Clayton *et al.*, 1998; Theyse *et al.*, 2000). Clinicians, using more sophisticated diagnostic tools, may more efficiently address the level of discomfort in horses caused by lameness.

Biomechanical analysis offers a method to objectively assess lameness and improve our understanding of gait abnormalities, adaptation to lameness, and improvements in response to therapy. This study aims to identify sensitive biomechanical variables to assist in the diagnosis of lameness, and to develop innovative graphical displays to facilitate the interpretation of biomechanical data. Furthermore, this study will investigate the effects of lameness on the variability of movement.

CHAPTER 2

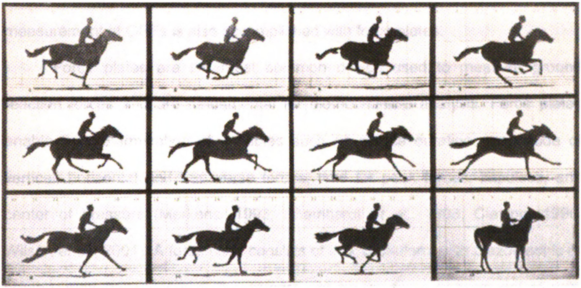
LITERATURE REVIEW

This chapter provides an overview of the history and development of equine locomotion analysis as a potentially advanced objective measure of locomotion. The epidemiology and mechanisms of musculoskeletal injury will be described, including conventional methods of diagnosis of lameness and potential applications of gait analysis in the diagnosis and evaluation of locomotor abnormalities in horses. Existing graphical displays of biomechanical data will be illustrated and, finally, biomechanical variability will be addressed in relation to its potential value in lameness assessment.

2.1 HISTORY AND TECHNIQUES OF EQUINE GAIT ANALYSIS

In 1872, Eadweard Muybridge performed a series of photographic studies of equine locomotion in Palo Alto, California, at a farm owned by Leland Stanford, the founder of Stanford University. After a period of traveling in Mexico and Central America, Muybridge returned to California and later continued his photographic work at the University of Pennsylvania. He used 24 single lens cameras that were trigged in series to capture sequential pictures of the locomotion of people, horses and other animals (Figure 2.1.1). In the meantime, in France, the physiologist and professor Jules-Etienne Marey was investigating equine gait analysis with different techniques. To discriminate between stance and swing phases Marey invented an "exploratory shoe" that detected an increase pressure in a small rubber balloon attached to the horse's foot that was designed for use on soft surfaces, while an "air-filled bracelet" was used on hard surfaces. To measure vertical movements of the withers and croup, he adapted two collapsible drums that were fastened to the withers and croup.

Figure 2.1.1 – Chronographic method of motion analysis in a galloping horse entitled "The horse in motion" (Muybridge, 1887).

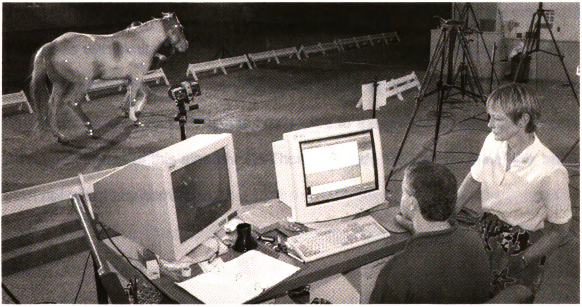


As the body falls and moves over the supporting foot, vertical, horizontal, and rotatory forces are generated on the floor that can be measured with appropriate instrumentation. The ground reaction forces (GRFs) are equal in magnitude and opposite in direction to the forces exerted by the weight-bearing limb. From knowledge of limb morphometrics, kinematics and ground reaction forces, the stress imposed on the joints and the muscular torque needed to control joint action can be calculated (Perry, 1992). In equine locomotion research, quantification of forces related to locomotion were first measured using pressure sensors attached to the shoe under the hoof and accelerometers attached to the limbs to measure the hoof-ground contact durations at the various gaits (Marey, 1873). Subsequently, strain gauge transducers were built into shoes of draft horses to evaluate horizontal and vertical forces between the hoof and ground (Bjorck, 1958). Vertical and horizontal components of forces acting on the hoof have subsequently been measured in Standardbreds (Quddus *et al.*, 1978) and Thoroughbreds (Geary, 1975; Bartel *et al.*, 1978). Today, measurement of GRFs is also accomplished with force plates.

Force plates are the most common device used to measure ground reaction forces and are fundamental for biomechanical analysis. Force plates enable the determination of variables such as stance duration, magnitude of vertical, horizontal and transverse forces, time for peak forces, impulses, and center of pressure (Merkens, 1993; Shamhardt *et al.*, 1993; Clayton, 1996; Wilson *et al.*, 2001). A force plate consists of a rigid platform with piezoelectric or strain gauge transducers at the corners. By having three sensors set at right angles (orthogonal) to each other, it is possible to measure the vertical load and the horizontal shear forces in longitudinal and medio-lateral directions. Through additional processing of these data, the related rotatory moments, center of pressure, and ground reaction force vectors can be determined (Perry, 1992).

Biomechanical research in animal locomotion has undergone tremendous technological innovations. For many years cinematography was the preferred technique for detailed quantitative analysis of locomotion, but it has some major limitations, including the long delay in obtaining results and the high cost of purchasing and processing cine film. Videography overcomes these limitations, but the early video systems had poor spacial resolution. Today, many measuring techniques are highly developed allowing precise and timely quantification of many aspects of animal movement. Automated and semi-automated gait analysis systems, such as SELSPOT, CODA-3, VICON and Motion Analysis, allow data to be collected fully automatically (Back *et al.*, 1995). This modern approach requires active (e.g. LEDs with SELSPOT), or passive (e.g. retro-reflective with Motion Analysis) markers to be attached on the body to the skin overlying anatomical landmarks on the bones. Opto-electronic or infrared cameras track the markers with their location being recorded into a computer (Figure 2.1.2).

Figure 2.1.2 – Gait analysis being performed using Motion Analysis System.



Although the automated biomechanical data collection systems provide many benefits for equine locomotion research, there are also some drawbacks. The high cost of purchasing and maintaining a gait analysis system and the technical skills required to operate it generally limits its use to the laboratory environment. The use of skin-based markers generates artifacts, especially at the proximal joints, due to skin displacement over the skeleton during locomotion (van Weeren *et al.*, 1990). Skin displacements can be as large as 12 cm, which is sufficient to change the entire shape of the angle-time diagrams (Back *et al.*, 1994). For joints such as the shoulder and elbow, data with skin displacement artifacts cannot be used for absolute angular computations or for measuring muscle or tendon lengths based on limb kinematics (Clayton & Schamhardt, 2001). This skin displacement has been quantified and correction algorithms have been developed for walking and trotting Dutch warmblood horses (van Weeren *et al.*, 1990; 1992). However, these correction algorithms are only valid for horses with similar conformation, moving at the same gait, and with the same speed. Despite conformational differences, these algorithms have been used in other breeds, such as in Thoroughbreds, due to the lack of more accurate data. Although the use of this algorithm in Thoroughbreds may not be ideal, it is better than not using any correction.

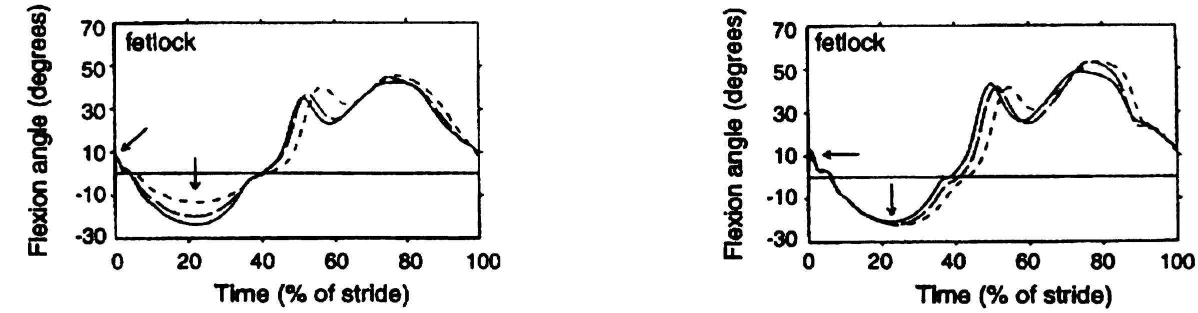
2.2 APPLICATIONS OF EQUINE GAIT ANALYSIS

The use of domestic animals for multiple tasks, such as work, pleasure and sport, emphasizes the necessity of selection methods for the fastest, strongest and most beautiful animals (Schamhardt *et al.*, 1993). Until recently, selection was based on subjective criteria, which can lead to unfair judgments (Leach, 1987; Ratzlaff, 1989). The need for more objective methods of evaluation was one of the factors that led to the explosion of equine locomotion research, that began in the 1970s and continues today (van Weeren, 2001). Studies included computation of internal forces in the digit (Bartel *et al.*, 1978); kinematic differences between distal portions of the forelimbs and hindlimbs (Back *et al.*, 1995), effects of trotting speed on muscular activity and kinematics (Robert *et al.*, 2002); effects of morphological variation on biomechanical data (Lewis *et al.*, 2002); description of navicular bone movement *in vitro* (van Dixhoorn *et al.*, 2002) and several others. Gait analysis uses biomechanical principles to make objective measurements of locomotion and provide a detailed quantitative description of movement patterns in humans and animals (Bartlett, 1997).

Biomechanics is defined as the science that examines forces acting upon and within a biological structure and the effects produced by such forces (Hay, 1982). Vertebrate locomotion is controlled by mechanical principles that are expressed in Newton's three Laws of Motion (see Gray, 1968). The First Law states that if the body of an animal is at rest relative to its environment, it can only be set in motion by the application of an external force, and, consequently, if an animal is to move its body by its own unaided efforts, it must elicit a force from its external environment. The Second Law states that the sum of all forces (ΣF) acting on a body of a given mass (m) equals the mass times acceleration (a) of that body (F = ma). The Third Law states that for every action there must be and equal an opposite reaction. Translated into biological terms, this can be expressed by saying that, in order to subject its body to a forward propulsive force, the animal must simultaneously exert an exactly equal, but opposite, backward force against its external environment (Gray, 1968).

Biomechanics uses two complementary approaches to study the body in motion: kinematics and kinetics (Barrey, 1999). Kinematics is the study of the geometry of motion, while kinetics is the study of internal (muscle activity) and external forces (e.g. ground reaction forces, GRF) acting upon the body (Nigg, 1999). Kinematic data are expressed as temporal (timing), linear (distance or displacement), and angular measurements that describe the movements of the body segments and joint angles. Within the past few years, computerized kinematic gait analysis has been used to study movement of clinically normal and lame horses (Barrey, 1999). Several investigators have described various kinematic variables in horses with normal gait patterns (Back *et al.*, 1995; Johnston *et al.*, 1996; Back *et al.*, 1996; Pourcelot *et al.*, 1997; Clayton *et al.*, 1998), with superior movement qualities (Holmström *et al.*, 1994; Morales *et al.*, 1998), and with specific abnormalities (Buchner *et al.*, 1995, 1996; Pourcelot *et al.*, 1997; Keegan *et al.*, 1998; 1997). The joint movement patterns of the equine limbs are important indicators of both physiologic locomotor capacity (Back *et al.*, 1994; Holmström *et al.*, 1994) and gait disturbances due to lameness (Buchner *et al.*, 1996; Keegan *et al.*, 1997). In 1994, Back *et al.* showed that some forelimb kinematic variables such as stride and swing duration, scapular rotation, maximal fetlock extension, and forelimb maximal retraction correlate well with judged scores for gait quality in young trotting Warmbloods. Head and trunk movements have been described as sensitive indicators of lameness in horses with fore and hind limb lameness (Peloso *et al.*, 1993; Buchner *et al.*, 1996). Furthermore, fetlock extension, carpal flexion and stride length have been shown to decrease with induced carpal lameness (Back *et al.*, 1993). In a model of supporting limb lameness, in each pain is induced by pressure on the hoof sole (Buchner *et al.*, 1995), the most striking changes were found in the pattern of the fetlock joint, where the maximal extension angle decreased with increasing lameness (Buchner *et al.*, 1996) (Figure 2.2.1), and in the coffin joint, where peak flexion in the first half of stance was reduced with each degree of lameness. Compensatory mechanisms in the contralateral limb were also found, where both fetlock extension and coffin flexion were increased (Buchner *et al.*, 1996).

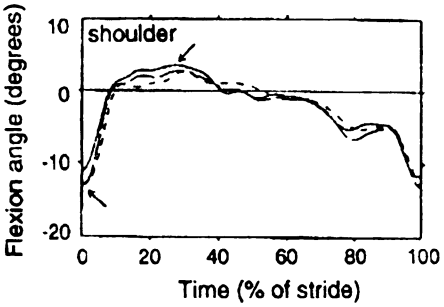
Figure 2.2.1 – Fetlock joint angle pattern of lame (left) and contralateral (right) forelimbs using a model in which lameness was induced by pressure on the hoof sole. ____ = lameness degree 0 (non-lame), _ _ _ = lameness degree 1, - - - = lameness degree 2 (Buchner *et al.*, 1996).

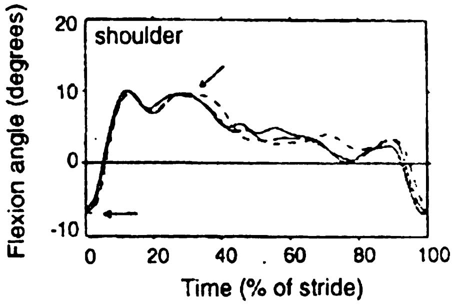


Arrows indicate the events selected by Buchner *et al.* (1996) for quantitative analysis

In contrast to the distal joints, the proximal joints are considered to play a more active role in lameness management. The movement of proximal joints is more dependent on muscular control than the distal joints, such as the fetlock, where passive support by the interosseus (suspensory) ligament is the most significant factor (Buchner, 2001). The shoulder normally flexes as the forelimb is loaded, and interestingly in the lame forelimb, this flexion was increased as a means of controlling the loading of the distal limb (Buchner *et al.*, 1996) (Figure 2.2.2).

Figure 2.2.2 – Shoulder joint angle pattern of lame (left) and contralateral (right) forelimbs. ____ = lameness degree 0 (non-lame), _ _ _ = lameness degree 1, - - - = lameness degree 2 (Buchner *et al.*, 1996).

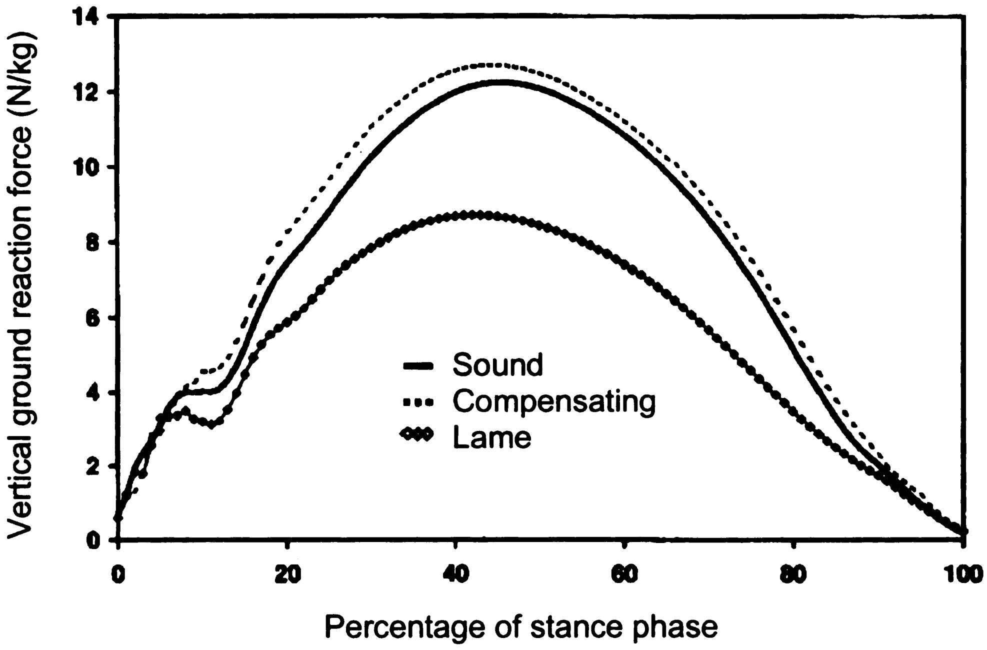




Arrows indicate the events selected by Buchner *et al.* (1996) for quantitative analysis

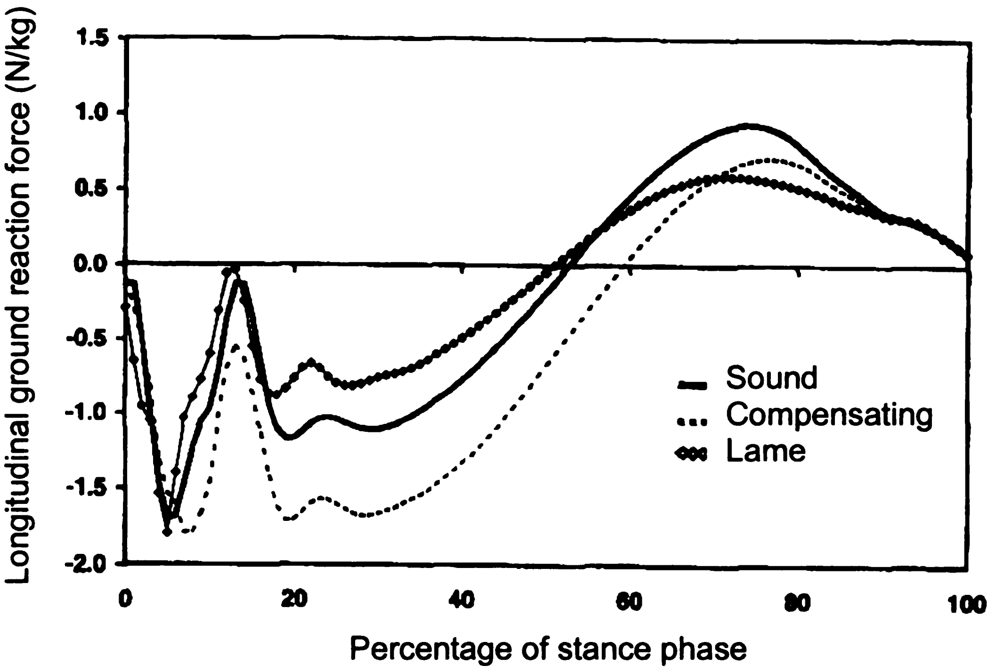
In regard to GRFs, the vertical force represents the supporting function of the limb. In sound horses, the vertical force has a peak magnitude of the order of 60% and 90% of the body mass at walk and trot, respectively (Clayton & Schamhardt, 2001). However, recent studies have shown that the vertical force in sound trotting horses can reach 110% of the body mass (Mullineaux & Clayton, in review). During trotting, the vertical force trace shows a small peak immediately after ground contact during the impact phase. The force trace then rises smoothly to peak approximately at the middle part of the stance phase. Subsequently, the vertical force decreases to lift off (Figure 2.2.3).

Figure 2.2.3 – Mean (n = 6) vertical ground reaction forces during the stance phase for sound horses (mean value for 2 forelimbs) and lame horses (lame and compensating forelimbs) with superficial digital flexor tendonitis (Clayton *et al.*, 2000).



The longitudinal force has a negative (braking) phase followed by a positive (propulsive) phase (Figure 2.2.4). The peak longitudinal force represents 10 to 15% of the horse's body mass at the walk and trot (Clayton & Schamhardt, 2001). Marked negative spiking occurs during the impact phase at the trot.

Figure 2.2.4 – Mean (n = 6) longitudinal ground reaction forces during the stance phase for sound horses (mean value for 2 forelimbs) and lame horses (lame and compensating forelimbs) with superficial digital flexor tendonitis (Clayton *et al.*, 2000).



Despite the rapid progress of equine locomotion research and the introduction of new concepts of gait analysis that enable the identification of gait abnormalities, the interpretation of results may be complex and further hampered by the large inter and intra-individual variability of subjects that leads to lack of statistical significance (van den Bogert & Schamhardt, 1993). Moreover, understanding of how the horse adapts to specific injuries in one or more limbs is still limited. Due to the complexity in the interpretation of results, increased type II error, and poor understanding of mechanisms of gait adaptation in response to specific injuries and lameness, it is clear that the study of factors affecting locomotion and lameness must be of high priority (Leach & Crawford, 1983).

2.3 MUSCULOSKELETAL INJURIES IN RACING THOROUGHBREDS

2.3.1 Epidemiological aspects

Musculoskeletal injuries are the most common condition afflicting racehorses (Rossdale *et al.*, 1985). In North American racing, the overall incidence of musculoskeletal injuries ranges from 3.3 to 7.3 per 1000 starts, depending on variables such as reporting criteria and degree of follow up (Hill, 2003). The rates for training injuries may be somewhat higher, although accurate acquisition and evaluation of these data is difficult (Mundy, 1996). Early studies demonstrated that lameness is the most common reason that horses in training failed to race (Jeffcott *et al.*, 1982; Rossdale *et al.*, 1985), accounting for 67% of days lost. As well as the discomfort and performance loss, lameness is estimated to cost the USA horse owning public approximately 678 million dollars per year (USDA, 2001).

The forelimbs are involved in 90% of the racing injuries (Peloso *et al.*, 1994), particularly in racing Thoroughbreds, with 95% of lameness occurring at the level of or distal to the carpus (Ross, 2003). The high incidence of injuries in the forelimb has been suggested to be due to the increased load on the forelimbs observed at canter and gallop, along with the cranial shift in the center of gravity promoted by the gait itself and the mass of the rider (Ross, 2003). Overall, the left forelimb is most frequently involved, with injuries particularly occurring in the turns. When raced in a counter-clockwise direction, horses are usually on the left lead in the turns and on the right lead during the straightaway (Palmer, 1986). It has been shown that the highest vertical force is on the lead forelimb at the gallop (Ratzlaff *et al.*, 1990), which increases the injury risk on the lead limb (Peloso *et al.*, 1994). Among the causes of lameness, 85.5% of all racing injuries occur from the carpus to the metacarpophalangeal joint (Peloso *et al.*, 1994), with the metacapophalangeal joint alone representing 14% (Rossdale, 1985).

Multiple risk factors are associated with mild to catastrophic (fatal) musculoskeletal injuries in racehorses. Increasing evidence suggests that pre-existing pathologic conditions could play a role in the development of injuries (Krook *et al.*, 1988; Stover *et al.*, 1992; Peloso *et al.*, 1994; Cohen *et al.*, 1997). Horses with lameness grading score of 1 and abnormalities of the suspensory ligament, diagnosed during pre-race physical inspections, were demonstrated to have odds of injury to the suspensory apparatus of the forelimb 34 times greater than horses with no abnormalities (Cohen *et al.*, 1997). Additional risk factors such as poor track design (Cheney *et al.*, 1973; Hill *et al.*, 1986; Clanton *et al.*, 1991) and variation in the number of days between races have been associated with injury (Stover *et al.*, 1992). Time interval between races of less than 3 weeks has been observed to increase the occurrence of injury (Stover *et al.*, 1992). Moreover, a strong perception exists in the racing industry that turf courses are safer than dirt courses. On the other hand, studies on the real influence of turf racing versus dirt racing on the incidence of musculoskeletal injuries in Thoroughbred racehorses have been criticized (Kobluck, 2003) based on a personal judgment that considers most of the horses racing on turf higher quality athletes, thus the data are not directly comparable.

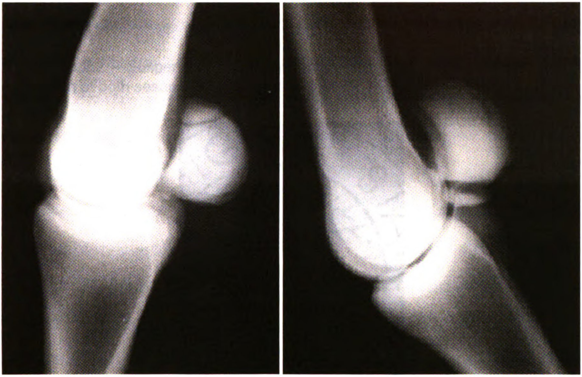
2.3.2 Mechanisms of musculoskeletal injury

Musculoskeletal injuries occur as a result of biomechanical stresses of abnormal intensity, duration, and frequency placed on bones, joints and attachments of the skeleton during race training and racing (Cohen *et al.*, 1997). The main locations of injuries in the skeleton are hyaline cartilage, bone, and fibrous tissues. There is increasing evidence that a significant proportion of fractures affecting Thoroughbred racehorses involve fatigue processes. Fatigue is a cumulative process. If the factors responsible for fatigue damage can be identified, they may be manipulated before progressing to a catastrophic conclusion (Riggs, 2002). A bone that is subjected to excessive cyclical loading will undergo fatigue and its material properties will be progressively eroded. If the rate of accumulation of damage is sufficiently rapid, the bone may be so weakened that it becomes unable to withstand the normal loads of day-to-day life (Riggs, 2002). If the intensity or frequency of loading is reduced, the bone may show an adaptive response rather than failure.

Mild to moderate injuries, which are considered the most frequent during races (Jeffcot *et al.*, 1982), may progress to a more severe injury when the stress overcomes the capacity of tissue repair (Estberg *et al.*, 1996). This stage of the pathology-injury spectrum includes symptomatic lesions of joint capsule injury;

degenerative joint disease; chip, slab, lateral condylar, phalangeal, and proximal sesamoid bone fractures (Figure 2.3.2.1); third carpal bone disease; bone spavin; dorsal metacarpal disease; flexor tendonitis; and suspensory desmitis.

Figure 2.3.2.1 – Apical (left) and basilar (right) proximal sesamoid fracture (White, 2002).



In contrast to mild to moderate injuries, catastrophic injuries are less common. Catastrophic injuries often involve a failure of the suspensory apparatus of the forelimbs (suspensory ligament and its branches, proximal sesamoid bones, and distal sesamoidean ligaments) (Figure 2.3.2.2). During exercise, fatigue of the proximal portion of the suspensory apparatus may allow excessive extension of the metacarpophalangeal joint, producing tensile forces that exceed the biomechanical tolerance of the supporting structures leading to failure of the bone or soft tissues (Hubert *et al.*, 2001) that compromise the support of the metacarpophalangeal joint (Estberg *et al.*, 1992; Jonhson *et al.*, 1994; Estberg *et al.*, 1996; Kane *et al.*, 1996). The weakest components of the suspensory apparatus are those most likely to fail. The proximal sesamoid bones are the weakest component of the suspensory apparatus in young racing horses, when the suspensory ligament has been strengthened with exercise (Bukowiecki *et al.*, 1987).

Figure 2.3.2.2 – Suspensory breakdown injury with a comminuted fracture and distraction of both sesamoid bones (Auer & Stick, 1999).

Racing injuries involving the fetlock joint may cause moderate to severe lameness depending on the etiology. Non-fracture injuries caused by acute or repetitive overload, such as synovitis, chronic proliferative (villonodular) synovitis, osteoarthritis, subchondral bone injury, and sesamoiditis, are associated with moderate lameness that may increase as the injury progresses (Stashak, 2002). Articular fragments at the dorsal or palmar aspects of the proximal phalanx; apical, abaxial, and basilar sesamoid fractures; and fragments from the sagittal ridge of the MCIII may cause a more pronounced and sudden lameness (Stashak, 2002). Major articular fractures that often lead to euthanasia, including sagittal and dorsal fractures; collateral avulsion injuries of the proximal phalanx, mid-body; abaxial or basilar fragments of the proximal sesamoid bones; and condylar fractures of MCIII promote severe lameness either at the end of or during a race (Stashak, 2002).

Videotape analysis of racing accidents suggests that injuries frequently occur when the lead limb is changed, the jockey uses the whip, or the horse is moving obliquely across the track (Ueda, 1991; Ueda *et al.*, 1993). Stumbling during race is associated with catastrophic, and career ending injuries (Cohen *et al.*, 1997). Physical interaction with another horse during the race is often associated with catastrophic injuries and injury of the superficial digital flexor tendon of the forelimb (Cohen *et al.*, 1997).

2.4 CLINICAL EVALUATION OF LAMENESS

Horses manifest locomotion abnormality by lameness, which may indicate structural or functional disorder in one or more limbs or in the back (Seeherman, 1999). This condition can be caused by trauma, congenital or acquired abnormalities, infection, metabolic disturbances, circulatory and nervous disorders, and any combination of these (Stashak, 2002).

Experience, acquired by years of clinical practice, working and learning from experienced practitioners, is required for accurate lameness evaluations (Ross *et al.*, 2003). More than that, the evaluation of lameness requires a detailed knowledge of anatomy, an understanding of kinematics, and an appreciation for geometric design and resultant forces (Stashak, 2002). The development of the skills required to become a true lameness diagnostician requires a thorough, somewhat methodical approach (Ross *et al.*, 2003). Equine practitioners carefully evaluate lameness following four main steps: (1) anamnesis; (2) identification of the lame limb or limbs through observation at rest and exercise; (3) palpation and manipulation of the lame limb or limbs to allow identification of the site of pain; and potentially (4) diagnostic anesthesia and imaging diagnostics to clarify the location of pain, the nature of the problem, and the extent of injury. The severity of lameness is categorized as mild, moderate, or severe, or by using a qualitative and semi-quantitative grading score system (e.g. Swanson, 1984; Table 2.4.1).

Table 2.4.1 – Lameness grading score system (Swanson, 1984).

GRADE	LAMENESS DESCRIPTION
0	Lameness not perceptible under any circumstances
1	Lameness difficult to observe; not consistently apparent regardless of circumstances (e.g., weight carrying, circling, inclines, hard surface)
2	Lameness difficult to observe at a walk or trot in a straight line; consistently apparent under some circumstances (e.g., weight carrying, circling, incline, hard surface)
3	Lameness consistently observable at a trot under all circumstances
4	Lameness obvious; marked nodding, hitching, and/or shortened stride
5	Lameness obvious; minimal weight bearing in motion or rest; inability to move

In addition to the severity, lameness is usually classified into one of four types: (1) supporting limb lameness is evident when the foot first contacts the ground or when the limb is supporting weight (stance phase). It is often caused by injury to bones, joints, soft tissue (e.g., ligaments and flexor tendons), motor nerves, and/or the foot. (2) Swinging limb lameness is seen when the limb is in motion and it is often caused by pathologic changes involving joints, muscles, tendons (primarily extensors), tendon sheaths, or bursae. (3) Mixed lameness is seen both when the limb is moving (swing phase) and when it is supporting weight (stance phase). It may involve any combination of the structures affected in swinging or supporting limb lameness. (4) Complementary or compensatory lameness occurs when pain in one limb causes uneven distribution of weight on another limb or limbs. This can produce lameness in a previously sound limb. For instance, lameness of the right forelimb may promote compensatory lameness in the contralateral forelimb and/or ipsilateral hindlimb (Stashak, 2002).

Identification of such types and severities of lameness requires an ability to recognize the subtle as well as the obvious signs, and to possess the knowledge to interpret the observations. The most convenient sensor is the trained eye of the practicing clinician, that permits assessment of the problem at any time and in any environment (Perry, 1992). Visual observations, along with the lameness score system, provide semi-quantitative information with good repeatability among experienced clinicians (Back *et al.*, 1993). However, there is considerable variation between clinicians with different levels of expertise (Keegan *et al.*, 1998) and poor correlation between the scores assessed by visual observations versus objective measures (e.g. GRFs) (Fuller *et al.*, 2002). The variability and inconsistency of subjective lameness evaluations justifies the need for development of objective ways to improve the evaluation of lameness in horses.

2.5 USE OF BIOMECHANICS IN LAMENESS EVALUATIONS

Some types of lameness cause pain during loading so the horse tries to minimize this pain by changing various aspects of the locomotion pattern (Buchner, 2001). These changes are manifested by asymmetries in temporal and spatial kinematics, as well as force distribution variables between the limbs (Clayton, 1987; 1988; Girtler, 1988). Biomechanical or gait analysis can detect these changes in the locomotion pattern. Variables such as stride length, stride duration, stance duration, peak vertical and longitudinal ground reaction forces, and joint angular kinematics can be used to detect gait abnormalities (Leach, 1983; Back *et al.*, 1993; Schamhardt *et al.*, 1993; Buchner *et al.*, 1996; Barrey, 1999; Peham *et al.*, 2001). However, disease specific changes in the locomotion pattern and mechanisms of lameness adaptation are still poorly described.

In some areas there are controversial findings, for example, in the effects of supporting limb lameness on temporal stride variables. Some researchers have described a shortening of the stance phase after induction of carpal lameness as a mechanism to diminish pain (Ratzlaff *et al.*, 1982), while others described a lengthening of the stance phase using the same model of lameness (Morris & Seeherman, 1987) or when lameness was induced by pressure on the hoof sole (Galisteo *et al.*, 1997), with both limbs kept on the ground longer (Buchner *et al.*, 1995; Keegan *et al.*, 1997; Back *et al.*, 1993; Galisteo *et al.*, 1997). In contrast to obvious supporting limb lameness, subclinical lamenesses do not show significant temporal deviations from the sound stride pattern (Buchner *et al.*, 1995).

Lameness can also be detected by changes in the ground reaction forces (Tietje, 1992; Buchner *et al.*, 1995). A decrease in both vertical (see section 2.3, Figure 2.2.3) and longitudinal (see section 2.3, Figure 2.2.4) ground reaction forces in the lame limb is observed, while a compensation of amplitudes of the non-affected limbs occurs (Gingerich *et al.*, 1979; Silver *et al.*, 1983; Merkens & Schamhardt, 1985, 1988). The lengthening in stance phase duration allows the impulse to be maintained with a lowest force amplitude (Morris & Seeherman, 1987). The decrease in braking horizontal force is suggested to be due to an ineffective deceleration of the limb (Morris & Seeherman, 1987).

Joint angle patterns are also influenced by lameness. Supporting limb lameness cause striking changes in the joint angle patterns especially at the distal joints such as the fetlock (see section 2.2, Figure 2.2.1) and coffin joints (Buchner *et al.*, 1996). Changes in joint angles usually correspond to the decrease in vertical GRF observed in the lame limb (Riemersma *et al.*, 1988; see section 2.2, Figure 2.2.3). Compensatory changes may be seen in the contralateral limb (Merkens & Schamhardt, 1988; Morris & Seeherman, 1987). Limb retraction and protraction angles also change with lameness to adjust to the orthopedic pain. After sole pressure-induced lameness, maximum protraction of the forelimb is greater than before the induction of lameness (Buchner *et al.*, 1996; Keegan *et al.*, 2000), while both lame and contralateral forelimbs are less retracted at the end of the stance phase (Buchner *et al.*, 1996).

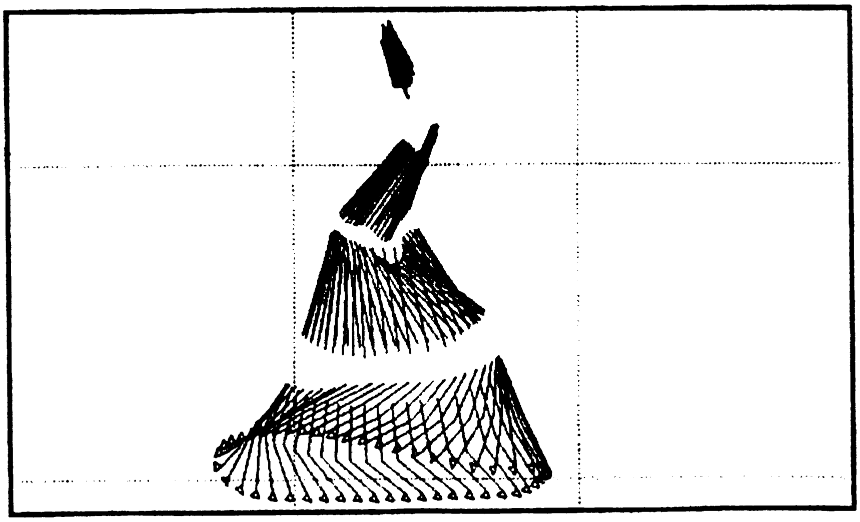
Advances in the equine biomechanics field have enabled detailed studies of experimentally induced lameness (Morris & Seeherman 1987; Merkens & Schamhardt 1988; Back *et al* 1993; Peloso *et* al. 1993; Buchner *et al.* 1995, 1996; Deuel *et al.* 1995; Clayton *et al.*, 2000) or naturally occurring lameness (Clayton, 1986; Williams, 2001; Peham *et al.*, 2001; Clayton *et al.*, 2002). Gait analysis provides a method of quantifying the horse's locomotion abnormality with reliable instrumentation and permanent record of fact. Consequently, the imprecision of subjective information is avoided, rapid and subtle events are captured, and printed records of the horse's motion pattern offer a reference base for interpreting improvement. In order to be more easily applicable, gait measuring techniques and the display of results should be simplified.

2.6 GRAPHICAL PRESENTATIONS IN GAIT ANALYSIS

Gait analysis produces voluminous numerical data that can overwhelm the investigator with numbers that are difficult to interpret. Therefore, numerical data are only useful after analysis in a manner that improves understanding and knowledge (Schamhardt *et al.*, 1993). One way to achieve a better level of understanding of gait analysis is through the use of graphs or diagrams.

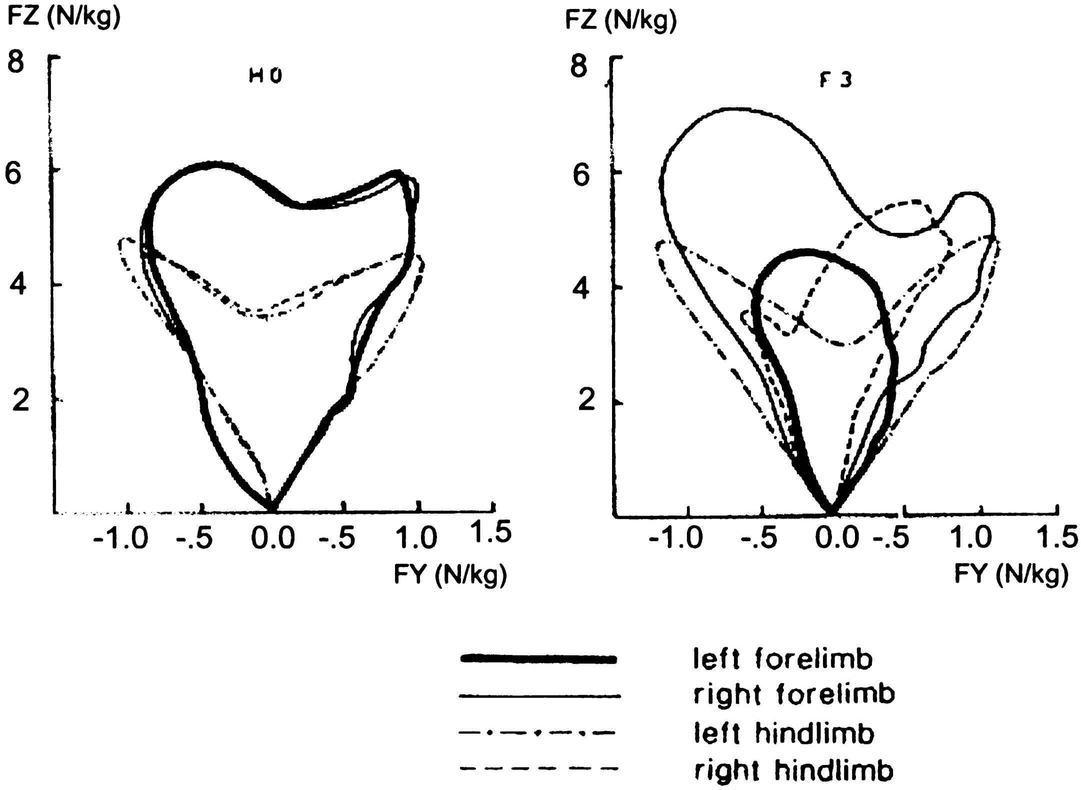
Basic locomotion information, such as the magnitude of the peak joint angles (flexion and extension), can be easily extracted from biomechanical data. However, the magnitude of joint motion as an independent item of information may not be sufficient to identify the gait abnormality, as the timing of motion in adjacent joints may be a critical factor (Perry, 1992). Graphical representations such as variable-variable plots can maximize information about the movement, suggest a specific gait abnormality, and facilitate understanding of the movement (Mullineaux *et al.*, 2000). For instance, joint angle-time diagrams (see section 2.2, Figures 2.2.1 and 2.2.2) can be used to describe coordination between joints of the equine forelimb, and they can be related to stick diagrams (Figure 2.6.1), which will improve the understanding of the movement the entire limb (Back *et al.*, 1995). Stick diagrams are used to illustrate the motion of the limb during the stride using lines to represent the limb segments (Barrey, 1999). Overall, stick diagrams facilitate recognition of left-to-right symmetry (or asymmetry) of movement in humans (Perry, 1992) and animals (Pourcelot *et al.*, 1997). Angle-angle diagrams, for instance, carpal-fetlock diagrams, have also been found to be useful in detecting forelimb coordination problems (Back *et al.*, 1995).

Figure 2.6.1 – Stick diagram of the forelimb of an individual horse trotting at a velocity of 4 m/s on a treadmill from left to right during a complete stride (Back *et al.* 1995).



Force data output is expressed in terms of forces in three mutually perpendicular planes, referred to as medio-lateral or transverse (F_x), craniocaudal or longitudinal (F_y) and vertical (F_z). The three force components are usually displayed separately as force-time diagrams (see section 2.2., Figures 2.2.3. and 2.2.4). Although used widely in biomechanics, these types of diagrams are difficult to interpret for pathological conditions because they give little indication of the effects that abnormalities have on the alignment and proximity of the force vectors relative to the joints of the distal limb, and the turning effects (torques) that they generate around those joints (Stallard, 2000). To permit a more immediately observable indication of the effects of these forces in a human or animal, methods of displaying and analyzing force vectors have been developed. A force vector is a line representing the magnitude and direction of a force. Although forces are three-dimensional, the vector may be shown in one plane (sagittal, frontal or transverse). In humans, force vector diagrams in a sagittal plane, also called butterfly diagrams due to their shape, are used in gait analysis to illustrate gait patterns in pathological conditions such as ostearthritis and hip disorders, and also to assess intrinsic and extrinsic variability of GRF within individuals (Rozendal *et al.*, 1985; Khodadadeh, 1988; Baumann *et al.*, 1992; Rabufetti & Frigo, 2001). In horses, they have been used to illustrate GRF patterns of Dutch Warmbloods at normal walk (Merkens *et al.*, 1985), and also to describe changes in GRF during different degrees of experimentally induced lameness at walk (Merkens & Schamhardt, 1988) (Figure 2.6.2). The use of these diagrams at trot for lameness diagnosis has not been described and their effectiveness for this purpose needs further investigation.

Figure 2.6.2 – Vector diagram (or vectordynamogram) of mean (n = 4) Fy-Fz force-force curves of all limbs during control section (H0) and moderate left forelimb lameness (F3) (Merkens & Schamhardt, 1988).



The use of sophisticated diagnostic tools, such as gait analysis, offers a means of quantifying lameness in horses. However, to be considered an auxiliary diagnostic tool, the resultant information needs to be illustrated effectively, thus providing clear evidence and better understanding of gait abnormalities, adaptation to lameness, and improvements through therapy. Graphical representations are a valuable tool to be used in gait analysis studies, especially to facilitate interpretation by clinicians who are not familiar with the analytical method. It is timely to focus equine locomotion studies on the development of more friendly ways to display numerical gait analysis data that will facilitate its use in a clinical setting.

2.7 VARIABILITY OF MOVEMENT

The movement of healthy humans is characterized by slight, but continuous, variation of the motion pattern (Yamada, 1995; Whitall & Getchell, 1996; van Emmerik & Wagenaar, 1996). This variation is an inherent component of movement both within (intra-subject) and between (inter-subject) subjects (Newell & Corcos, 1993). Every movement pattern is constrained by peripheral sources of variation such as morphological, environmental and mechanical (Bernstein, 1967; Higgins, 1977). Equine movement is also subjected to these sources of variation. Although a small variation coefficient (2%) of kinematic parameters is described within horses, the variation between horses is 2 to 3 times greater (Drevemo *et al.*, 1980). Sound horses are considered to have stable biomechanical variables, so the analysis of a relatively small number of strides becomes representative of the gait pattern. Due to this gait repeatability, it has been suggested that the analysis of 3 to 5 strides per horse is sufficient and representative of both kinematic (Drevemo *et al.*, 1980) and GRF (Schamhardt, 1996) patterns. However, in lame horses, the variability phenomenon has been poorly described.

Variability is suggested to have detrimental effects on biomechanical research. For instance, within and between subjects variation may affect the reliability of individual scores and significantly affect the statistical power of an experiment (Bates *et al,* 1996; Dufek *et al.*, 1995). The addition of trials can be used to control within subject variability, or to control between subject variability when subjects perform the same task in a similar manner (Dufek *et al.*, 1995). A more difficult situation arises when the source of variation is due to individuals using different solutions (strategies) to accomplish the same task. A strategy is defined as a selected neuromusculoskeletal solution for the performance of a task. Humans select a strategy based on previous experiences, their perceptions, and the resulting expectations (Dufek *et al.*, 1995). Considerable experimental evidence in support of individual strategies can be found in the research literature (Bates *et al.*, 1979; Loslever, 1993; Reinschmidt & Nigg, 1995). Performance differences (between subject variability) resulting from different strategies threaten the external validity of a group design and often lead to false support for the null hypothesis (Bates, 1989). Given these concerns, a possible approach for avoiding these potential problems is to combine group and single-subject designs to gain additional insight into the research problem of interest (Dufek *et al.*, 1995).

Single-subject, single case, and "n = 1" are all names for experimental designs that involve one subject observed over time, while some variable or factor is manipulated. The concept of single-subject analyses is not new. Historically, the intensive study of individual human behavior in the areas of psychology, psychiatry, and physiology began in the mid 1980's (Barlow & Herson, 1984). The methodology often consisted of making repeated response measurements to different stimuli. The results from these types of individual studies produced important findings that, with adequate replication, often provided indications for general results (Bates, 1996). As mentioned by Bates

(1996), the basic rationale for single-subject evaluation is simple: individuals are unique, no two individuals are alike. Overall, this type of analysis intends to overcome the effects of the individual selection of strategies to perform the same task. Variability between horses affects the response to certain interferences, such as drug treatment and shoeing, which differ qualitatively and quantitatively in different animals (Clayton & Schamhardt, 2001). Impressive libraries of statistical routines have been developed to extract trends in the data, to detect differences between groups, or to identify a statistical significant response to a certain treatment. In addition, the majority of equine locomotion studies are based on a rather small number of subjects, which may be insufficient to give the required power for a statistical analysis (Clayton & Schamhardt, 2001). The individual locomotion responses, along with the limited number of subjects available in equine biomechanical studies, emphasize the rationale for the implementation of single-subject analysis as an additional analytical method.

More recently, in the area of human movement science, there has been a resurging interest in the individual and, therefore, within individual variability. It has been suggested that variability has a functional role to play in human movement (Wheat *et al.*, 2002) and it is fundamental for changes in the coordination between body segments (Kelso, 1995). In addition, variability was suggested to play a role in lower extremity coordination that attempts to attenuate the large impact shocks present during the stance phase of running, thus playing also an important role in the prevention of injury (Heiderscheit *et al.*, 1999). In 1994, Buchner *et al.* used variability to characterize the stability of motion as a parameter for habituation of horses on the treadmill. All horses in his study showed within subject variation in stride variables. Variability has also been used to determine the optimum speed for lameness evaluation on the treadmill (Drevemo *et al.*, 1980; Peham *et al.*, 1998) and as an indicator of orthopedic pain (Peham *et al.*, 2001). In contrast to the high variability observed in running humans (Heiderscheit *et al.*, 1999), horses with orthopedic pain are described to have low stride variability (Peham *et al.,* 2001). Peham *et al.* suggested that this low variability could be associated with the optimization of compensatory mechanisms to reduce pain, and concluded that stride variability is an individual parameter of lameness. This study represents a starting point for further investigation of the function of variability in equine locomotion in lame and sound conditions.

RESEARCH OBJECTIVES

1. To identify sensitive biomechanical variables to be used in the diagnosis of fetlock joint lameness
2. To investigate variability in gait measures of Thoroughbred horses with fetlock injury and to compare the variability of sound subjects at the trot
3. To explore the use of graphical representations of biomechanical data for lameness detection

HYPOTHESES

H_1 : Biomechanical variables are sensitive to detect lameness in Thoroughbred horses with fetlock joint injury.

H_2 : Lame horses have less movement variability than sound horses.

CHAPTER 3

METHODS OF INVESTIGATION

3.1 SUBJECTS

Five lame Thoroughbred horses (group 1), with a history of career ending unilateral racing injury in the metacarpophalangeal (fetlock) joint of the forelimb, were selected for inclusion in this study (Table 3.1). An experienced clinician performed lameness evaluation and attributed a standard lameness score (Stashak, 1996) for each subject. Radiological study of the affected metacarpophalangeal joint area was performed and the final diagnosis was determined (Table 3.1).

Five sound horses were subjected to the same lameness evaluation protocol and included as a control group (group 2) (Table 3.2). All horses were used with approval of the Michigan State University All University Committee on Animal Use and Care (AUF#07/01-113-00).

Table 3.1 – Descriptive characteristics and lameness diagnosis of subjects from group 1 (R = right; L = left).

Subject	Age (years)	Mass (kg)	Height (m)	Injured forelimb	Lameness score	Lameness diagnosis
1	3	456	1.55	L	3	Basilar fracture of the lateral proximal sesamoid bone
2	4	484	1.61	R	2	Basilar fracture of the medial proximal sesamoid bone
3	4	430	1.58	R	2	Apical fracture of the lateral proximal sesamoid bone
4	6	517	1.66	L	2	Severe degenerative joint disease with exostosis around the fetlock joint
5	4	475	1.60	R	2	Degenerative joint disease of the fetlock joint

Table 3.2 – Descriptive characteristics of subjects from group 2.

Subject	Breed	Age (years)	Mass (kg)	Height (m)
1	Thoroughbred	18	508	1.56
2	Thoroughbred	13	505	1.6
3	Thoroughbred	15	537	1.58
4	Warmblood	6	586	1.6
5	Warmblood	6	518	1.56

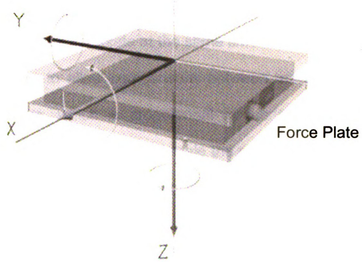
3.2 DATA COLLECTION PROTOCOL

The testing area consisted of a runway covered with high-density rubber matting, into which a 60 cm x 120 cm^2 force plate (AMTI LG6, AMTI, Watertown, MA) was embedded. In addition to the force plate, the collection area was equipped with an infrared gait analysis system consisting of 6 Falcon cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and a capture volume of 5 x 2 x 3 m. The equipment allowed three-dimensional ground reaction force (GRF) and kinematic data to be collected simultaneously throughout one complete stride (hoof contact to hoof contact) as the horse moved along the runway.

Calibration of the system was performed using a ‘seed and wand’ calibration method (Eva RT 3.2 User’s Manual Motion Analysis Corporation, 2002). The wand was 1 m in length with three retro-reflective, spherical markers (38 mm diameter). The calibration process accounted for any geometric distortion the camera lenses might have throughout the entire capture volume. The location of the force plate was obtained by placing retro-reflective spherical markers at each corner of the force plate. The three-dimensional component of the GRF was adjusted to zero and the sensitivity matrix was adjusted to account for “cross-talk” between the transducers, thus improving the force measurement accuracy. The coordinate system used to measure GRF and kinematic data consisted of transverse (X), longitudinal (Y) and vertical (Z) axes (Figure 3.2.1).

The positive directions were upward for the vertical force, cranially for the longitudinal force, and laterally for the transverse force.

Figure 3.2.1 – Coordinate system used during GRF and kinematic data collection.



Retro-reflective, spherical markers (25 mm) were attached on the lateral aspect of the forelimbs overlaying the following landmarks: attachment of lateral collateral ligament of the elbow joint on distal humerus (1 = elbow), distal edge of ulnar carpal bone midway between lateral styloid process of radius and proximal third metacarpus (2 = carpus), distal end of third metacarpus at attachment of lateral collateral ligament of metacarpophalangeal joint (3 = fetlock), hoof wall at the heel (4 = heel) and hoof wall at the toe (5 = toe). These markers allowed further determination of carpus, fetlock and coffin joints flexion and extension angles.

Markers 2 and 3 represented the approximate centers of the rotation of carpal and metacarpophalangeal joints in the sagittal plane. The flexion and extension angles were measured at the intersections of the segment lines at the center of rotation of each forelimb joint. The location of the distal interphalangeal (coffin) joint center of rotation was determined radiographically (see session 3.3).

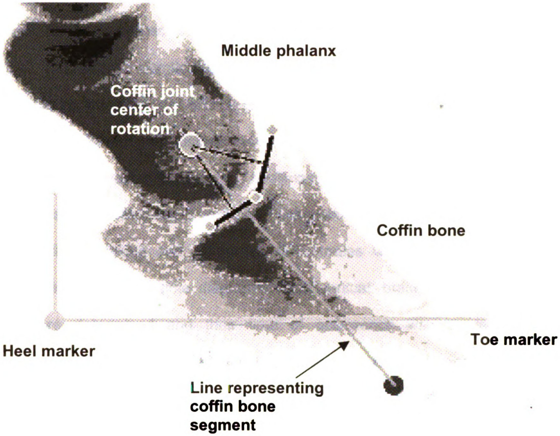
Five successful trials were collected for each limb separately, in which the forelimb being analyzed was fully on the force plate throughout its stance phase with no other limb on the force plate at the same time. Velocity was normalized to the horse's body size to allow comparisons between horses of different sizes. Height at the withers, which is proportional to the segment lengths of the forelimbs and hindlimbs, was applied to scale the gait variables (Khumsap *et al.*, 2002). Overall, the horses' trotting velocity was within a range of 3.0 to 3.3 $m.s^{-1}$. GRF and kinematic data were collected at frequencies of 1200 Hz and 120 Hz and filtered using 40 Hz and 15 Hz Butterworth low-pass filters, respectively (Clayton *et al.*, 2000). The GRFs were synchronized with the kinematic data. Subsequently, the data were normalized to the horse's body mass and to stride duration to facilitate further comparisons between horses.

Correction algorithms were not applied to the kinematic data to account for skin displacement because skin displacement for markers distal to the humerus are small enough to be ignored (e.g. carpal and fetlock joints) (van Weeren *et al.*, 1988; 1992).

3.3 DATA ANALYSES

Following data collection, 5 mm metal spheres were attached to the hoof wall at the exact location of heel and toe markers. Latero-medial radiographs of the hoof were taken from right and left forelimbs and later scanned to a computer. The radiographs with the two reference markers at the heel and toe were loaded into custom software (Radcof, Mary Anne McPhail Equine Performance Center, East Lansing, MI) that determined the approximate location of the center of rotation of the coffin joint. Two chords were drawn across the articular surface of the coffin bone. The software constructed perpendicular lines from the middle of each chord towards the center of the middle phalanx. The intersection of these lines represented the center of rotation of the coffin joint (Figure 3.3.1). The location of the center of rotation of the coffin joint was then translated into a coordinate system (x, y) and located relative to the position of the heel and toe markers in each frame throughout the stride.

Figure 3.3.1 – Latero-medial radiograph of the hoof showing schematic determination of the coffin joint center of rotation.



GRF and kinematic data for the forelimbs were analyzed using a custom code written in Matlab® 6.1 (The MathWorks Inc, Natick, MA, USA). The code accounted for time normalization to 101 data points from hoof contact to hoof contact using cubic spline interpolation, and location of the coffin joint center of rotation for each frame (coordinates extracted from Radcof software).

Joint angle measurements were calculated for each trial in a sagittal plane on the anatomical flexor side of the forelimb joints. Flexion and extension were defined as a decrease and increase in the angle value, respectively. Joint angle traces, maximum extension and maximum flexion were obtained through angle-time diagrams, and their time of occurrence was expressed as percent of stride duration. Stride variables such as stride duration (seconds), stride length (meters) and stance duration (percentage of stride) were also determined. Kinegrams, an adaptation of stick figures, were used as graphical displays for kinematic data. Kinegrams illustrate the locomotion pattern, and may assist in the detection of asymmetries between the forelimbs. Changes in variability within the kinematic variables were also investigated using standard deviation.

Vertical, braking and propulsive GRF traces were primarily obtained through the use of force-time diagrams. Peak vertical, braking and propulsive GRFs were determined and their time of occurrence was expressed as percentage of stance duration. Vertical, braking and propulsive impulses were calculated by time integration of the force curves. GRF peaks (N) and impulses (Ns) were normalized to body mass where they were expressed as N/kg and Ns/kg, respectively. In addition to force-time diagrams, a novel graphical display was used in an attempt to improve the recognition of the lame forelimb. Force vector diagrams were used to represent ground reaction forces in a method adapted from humans (Rozendal *et al.*, 1985; Khodadadeh, 1988) and horses at walk (Merkens *et al.*, 1985). These vector diagrams were applied in horses at trot for the diagnosis of lameness. Changes in variability of GRF variables were also investigated using standard deviation values.

3.3.1 Statistical analyses

The data were analyzed using two different statistical procedures, group mean differences, and single-subject analysis. The mean value for each variable was determined by averaging the 5 successful trials recorded for each subject. Subject mean values were averaged to calculate mean values. Subsequently, group mean differences within group 1 ("mean lame" versus "mean contralateral") and between groups 1 and 2 ("mean lame" versus "mean sound"; "mean contralateral" versus "mean sound") were determined using dependent t-tests. Single-subject analysis using dependent t-tests was performed for each variable in the study, comparing lame and contralateral forelimbs with the data gathered from the 5 trials for each forelimb. Dependent t-tests were used for the analyses, because the data for right and left forelimbs were collected during different trials, so they were not paired. The rationale for the use of single-subject analysis arises from the high variability between subjects, which threatens the reliability of the group statistical analysis by increasing type II error.

In addition, variability associated with the kinematic and GRF variables was also analyzed. Mean differences in standard deviation between "SD lame" and "SD contralateral" within group 1 were determined using paired t-tests. The same procedure was performed to determine mean differences in standard deviation between groups 1 and 2 ("SD lame" versus "SD sound", "SD contralateral" versus "SD sound").

The type I error was set at 5% ($p<0.05$) for all statistical analyses performed. The assumption of normality was met in the majority of variables for lame (lame and contralateral forelimbs) and control (sound forelimbs) groups. Non-normally distributed data were only found in stance duration for lame forelimb, propulsive impulse for contralateral forelimb and stride length for lame and contralateral forelimbs (Shapiro-Wilk > 0.05). Only one variable, stance duration between lame and contralateral forelimbs, was found to violate homogeneity of variance (Levene's test > 0.05). Despite these few violations, inspection of the means and standard deviations supported the results of the independent t-tests. Consequently, the normality and homogeneity of variance were considered not to deter accurate inferential statistical analyses.

CHAPTER 4

RESULTS

In the angle-time and force-time diagrams in this chapter, sound, lame and contralateral conditions will be displayed as lines in solid black, solid gray and gray with circles, as follows:

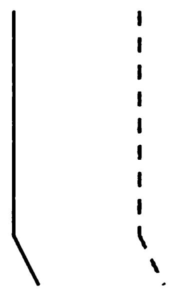
Contralateral

Lame

Sound

Kinegrams will have the lame and contralateral forelimbs displayed as dashed gray and solid black lines, respectively:

Contralateral



Lame

4.1. KINEMATICS

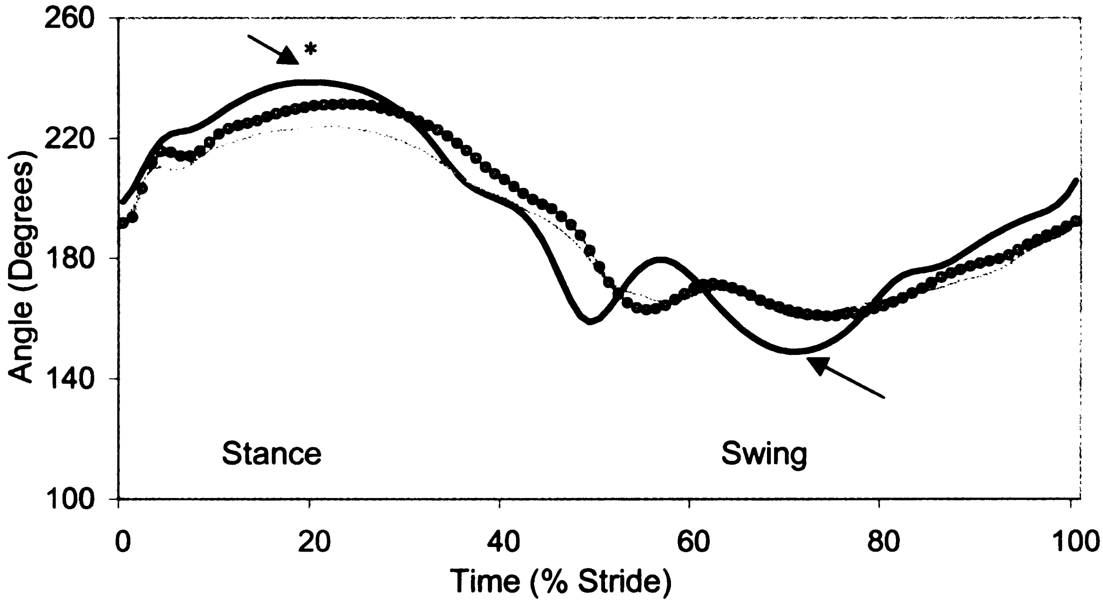
Differences in joint angles between groups were restricted to maximum extension of the fetlock joint (Table 4.1.1). Significant differences ($p<0.05$) within group 1 ("mean lame" versus "mean contralateral" forelimb) were not found, however, significant differences ($p<0.05$) between means of group 1 and group 2 were observed, where the maximum extension of the fetlock joint of the "mean lame" was significantly smaller (-19°) than the "mean sound" forelimb (Figure 4.1.1).

Table 4.1.1 – Mean (SD) joint angles for lame (L) and contralateral (C) forelimbs of the lame horses (group 1), and for the "mean sound" forelimb of the control horses (S; group 2).

Joint	Subject	Maximum extension (degrees)		Maximum flexion (degrees)	
		L	C	L	C
Carpus	1	183(0.7)*	187(1.5)	105(2.2)*	114(1.4)
	2	186(0.5)*	187(0.6)	117(1.7)*	114(1.4)
	3	185(0.7)*	184(0.5)	109(1.2)	108(1.7)
	4	194(1.1)*	192(1.2)	114(5.8)*	123(1.3)
	5	188(0.4)	188(0.2)	115(1.1)*	123(1.3)
	Group 1	187(4.2)	188(2.9)	112(4.9)	116(6.5)
	Group 2 (S)	187(4.1)		114(5.3)	
Fetlock	1	221(1.7)*	236(0.5)	143(8.0)	151(2.0)
	2	217(0.4)	217(0.4)	140(2.8)	139(9.0)
	3	237(0.4)*	240(0.3)	150(2.7)	155(6.7)
	4	207(0.7)*	233(1.1)	160(1.4)	159(1.7)
	5	218(1.4)*	234(1.0)	146(1.2)*	158(3.1)
	Group 1	220(10.8)[a]	232(8.8)	148(7.8)	152(8.1)
	Group 2 (S)	239(6.0)		147(4.3)	
Coffin	1	240(1.7)*	225(0.7)	177(8.9)	168(1.6)
	2	228(1.1)*	224(1.5)	171(0.7)	170(10.1)
	3	219(0.6)*	231(1.4)	165(1.3)	163(3.2)
	4	226(1.7)*	212(1.2)	187(3.3)*	171(1.3)
	5	224(1.5)*	198(3.5)	164(3.7)*	150(3.7)
	Group 1	227(7.8)	218(13.1)	173(9.5)	164(8.6)
	Group 2 (S)	221(4.8)		172(2.9)	

* Significant single subject difference between L and C forelimbs ($p<0.05$)
[a] Significant group mean difference between L and S forelimbs ($p<0.05$)

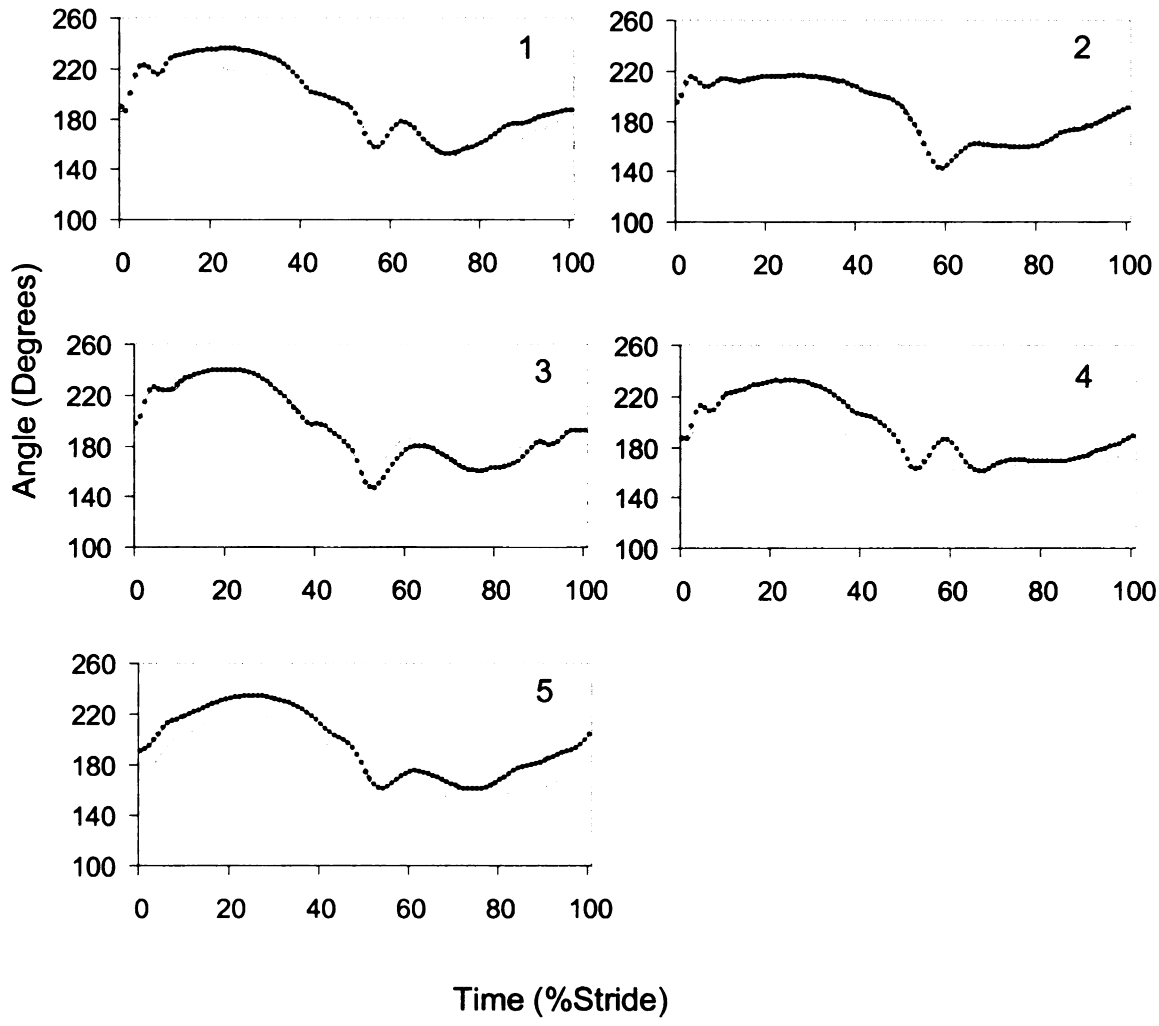
Figure 4.1.1 – Fetlock joint angle for the "mean lame" (solid gray line) and "mean contralateral" (gray line with circles) forelimbs of the lame horses (group 1), and for the "mean sound" (solid black line) forelimb of control horses (group 2).



Arrows indicate the events selected for analysis (maximum extension in stance phase, and maximum flexion in swing phase)
* Significant group difference between "mean lame" and "mean sound" forelimbs ($p<0.05$)

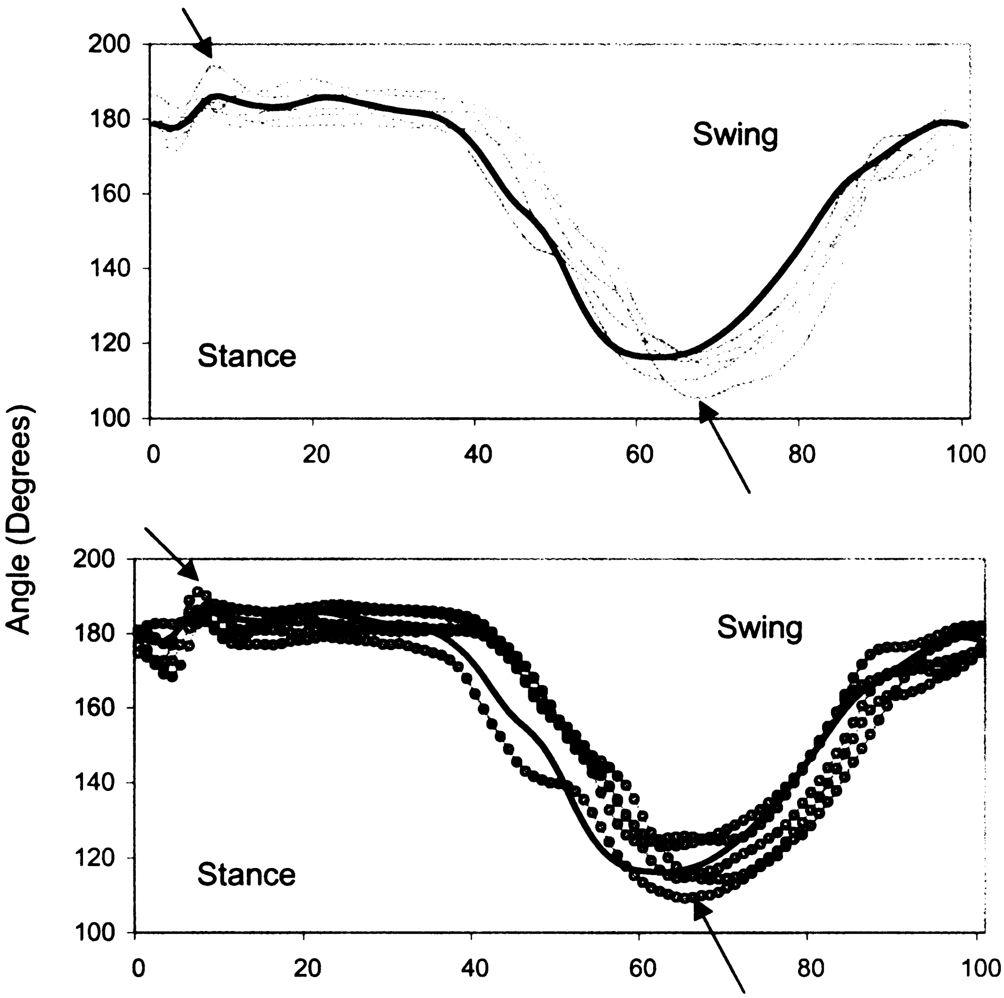
Single-subject analysis demonstrated that the lame forelimb of the majority of the subjects (horses 1, 3, 4 and 5) had significantly ($p<0.05$) smaller maximum extension of the fetlock joint than the contralateral limb, whereas in subject 2 there was little difference between limbs (Figure 4.1.2). The largest reduction in fetlock extension was seen in subject 4, which also had mechanical limitation of joint mobility, which resulted in 207° of maximum fetlock extension in the lame limb against 233° in the contralateral forelimb. The angle-time diagram (Figure 4.1.2) shows this remarkable reduction in the range of motion of the fetlock joint throughout the stride, where the joint trace of the lame limb is flattened when compared to the contralateral and sound forelimbs. In cases of moderate degenerative joint disease (e.g. subject 5) and proximal sesamoid fracture (subjects 1 and 3), the reduction in fetlock extension is also evident but not as prominent. Subject 2 did not demonstrate major differences between lame and contralateral limbs, but both limbs had reduced maximum extension of the fetlock joint.

Figure 4.1.2 – Fetlock joint angles for lame (solid gray line) and contralateral (gray line with circles) forelimbs of the lame horses (group 1).



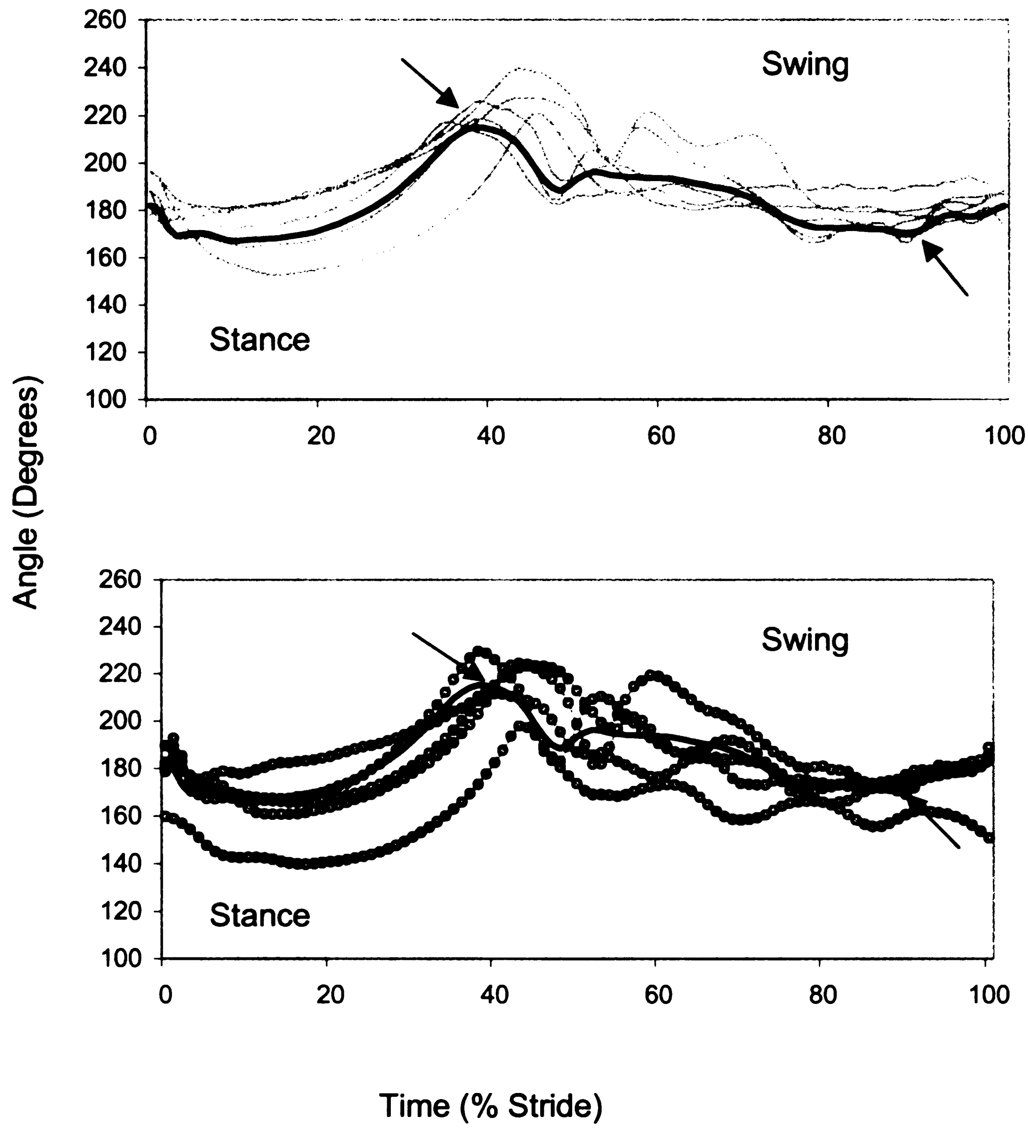
No group mean differences within group 1 or between groups 1 and 2 were observed at the carpal and coffin joints. However, considerable variation between subjects evident in the carpal and coffin joints traces (Figures 4.1.3 and 4.1.4) may have compromised the statistical power.

Figure 4.1.3 – Carpal joint traces for "mean sound" (solid black line) and the 5 trials for lame (solid gray lines; above) and contralateral (gray lines with circles; below) forelimbs of the lame horses (group 1).



Arrows indicate the events selected for analysis (maximum extension in stance phase and maximum flexion in swing phase)

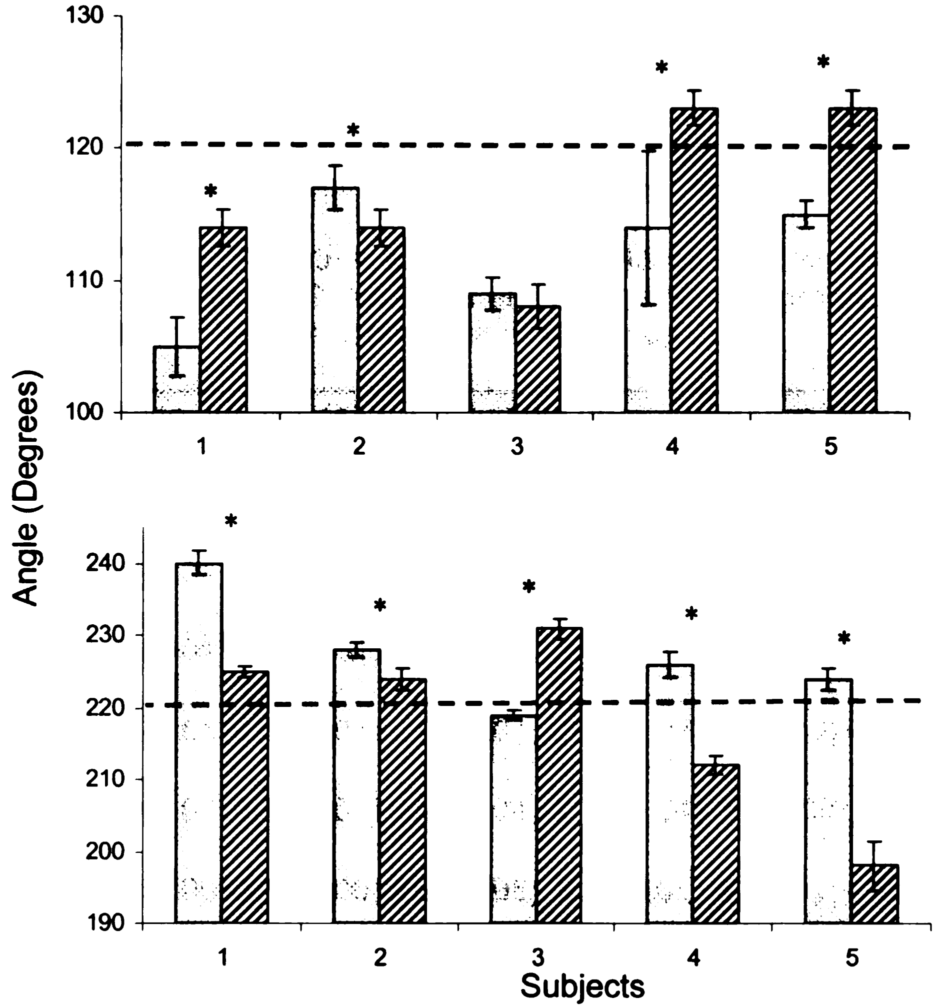
Figure 4.1.4 – Coffin joint traces for "mean sound" (solid black line) forelimb of the control horses (group 2) and the 5 trials for lame (solid gray lines; above) and contralateral (gray lines with circles; below) forelimbs of the lame horses (group 1).



Arrows indicate the events selected for analysis (maximum extension in stance phase and maximum flexion in swing phase)

Single-subject analysis detected differences in carpal and coffin joints between lame and contralateral forelimbs of subjects from group 1 (Table 4.1.1). There was no standard movement pattern between lame and contralateral forelimbs. Indeed, the relationship between the forelimbs was remarkably individual even for the subjects with the same type of injury (e.g. subjects 1, 2 and 3; see Figure 4.1.5).

Figure 4.1.5 – Carpal maximum flexion (above) and coffin maximum extension (below) angles ± SD for lame (gray shading) and contralateral (striped shading) forelimbs of the lame horses (group 1).



* Significant single-subject difference between lame and contralateral forelimbs ($p<0.05$)
Dashed horizontal lines = "mean sound" forelimb

In regard to stride variables, both "mean lame" and "mean contralateral" forelimbs demonstrated a significantly longer (p<0.05) stance phase duration compared to the "mean sound" forelimb. Along with longer stance phase, lame horses also showed a significantly shorter (p<0.05) stride length than the "mean sound" forelimb (Table 4.1.3). Three subjects (horses 2, 3 and 5) demonstrated single-subject differences in stance duration. Stance duration was significantly longer (p<0.05) on the lame forelimb compared to the contralateral forelimb in subjects 2 and 5, while subject 3 showed the contrary.

Table 4.1.3 – Mean (SD) stride duration, stride length and stance duration for lame (L) and contralateral (C) forelimbs of the lame horses (group 1), and for the "mean sound" forelimb of the control horses (S; group 2).

Subject	Stride duration (s)		Length (m)		Stance (% of stride)	
	L	C	L	C	L	C
1	0.70(0.01)	0.69(0.01)	2.18(0.05)	2.17(0.04)	47(0.02)	52(0.01)
2	0.68(0.01)	0.66(0.01)	2.20(0.02)	2.17(0.10)	53(0.00)*	48(0.02)
3	0.61(0.01)	0.63(0.01)	2.02(0.01)	2.01(0.03)	46(0.00)*	54(0.00)
4	0.70(0.01)	0.71(0.00)	2.19(0.04)	2.15(0.04)	51(0.00)	49(0.04)
5	0.72(0.00)	0.72(0.00)	2.20(0.05)	2.15(0.04)	47(0.01)*	46(0.00)
Group 1	0.68(0.05)	0.69(0.04)	2.16(0.07)[a]	2.13(0.07)[b]	49(0.03)[a]	50(0.03)[b]
Group 2 (S)	0.71 (0.03)		2.28 (0.09)		43 (0.01)	

* Significant single-subject difference between L and C forelimbs (p<0.05)
[a] Significant group mean difference between L and S forelimbs (p<0.05)
[b] Significant group mean difference between C and S forelimbs (p<0.05)

4.2. GROUND REACTION FORCES AND IMPULSES

Overall, the "mean lame" forelimb demonstrated significantly ($p<0.05$) smaller peak vertical GRF than the "mean sound" forelimb (Table 4.2.1; Figure 4.2.1).

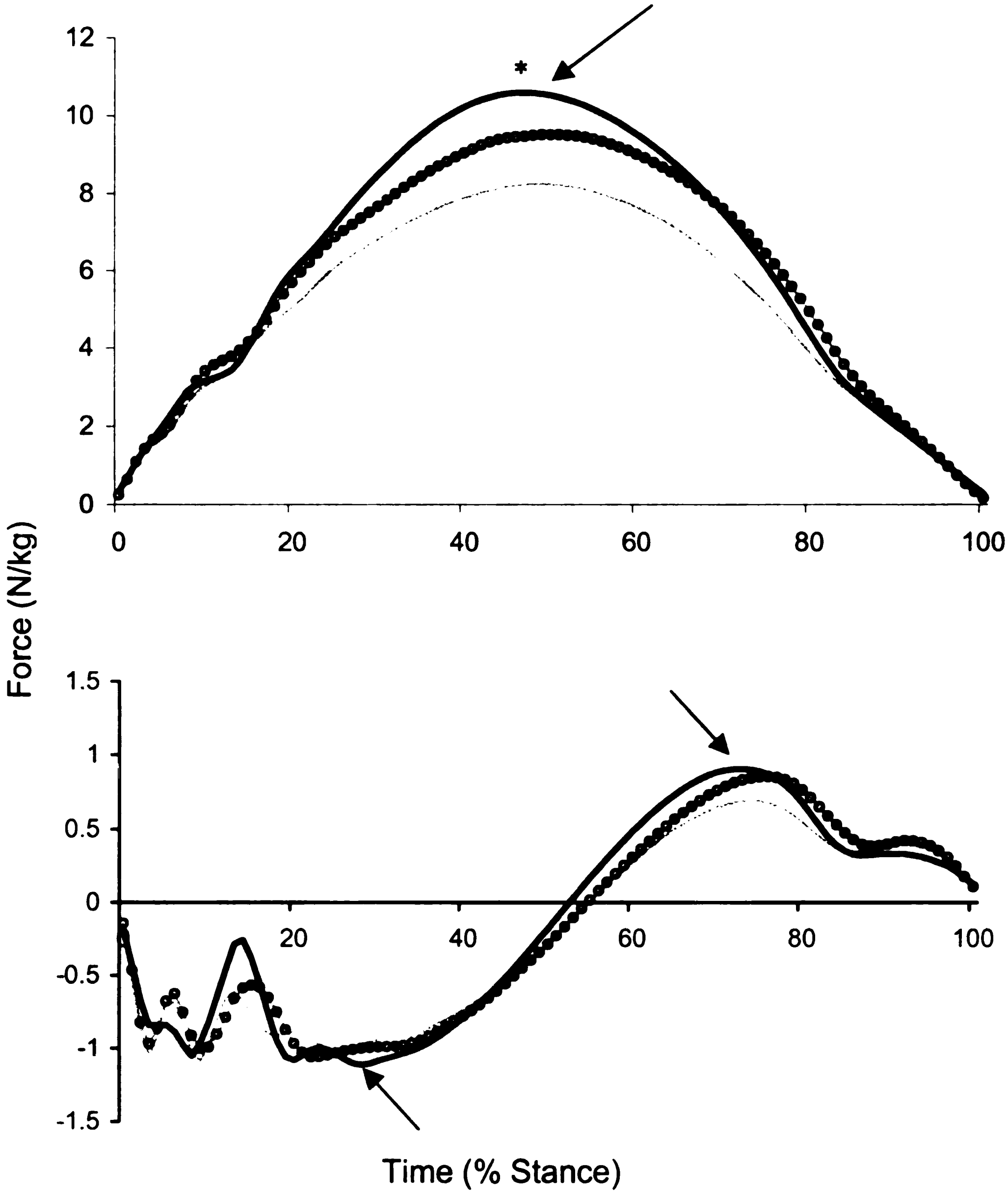
Table 4.2.1 – Mean (SD) peak vertical, braking and propulsive GRFs for lame (L) and contralateral (C) forelimbs of the lame horses (group 1), and for the "mean sound" forelimb of the control horses (S; group 2).

Subject	Peak Vertical Force ($N.kg^{-1}$)		Peak Braking Force ($N.kg^{-1}$)		Peak Propulsive Force ($N.kg^{-1}$)	
	L	C	L	C	L	C
1	7.26(0.3)*	9.88(0.2)	-0.89(0.2)	-1.27(0.5)	0.72(0.1)	0.98(0.3)
2	7.36(0.1)	7.48(0.2)	-1.37(0.3)*	-0.56(0.2)	0.33(0.1)*	0.84(0.1)
3	9.34(0.1)*	10.55(0.2)	-0.71(0.4)*	-1.20(0.1)	0.95(0.1)*	0.54(0.1)
4	9.36(0.1)	9.17(0.3)	-1.27(0.2)*	-0.69(0.1)	0.52(0.1)*	1.02(0.1)
5	8.09(0.1)*	10.51(0.1)	-0.83(0.1)*	-1.35(0.1)	0.71(0.0)*	0.92(0.0)
Group 1	7.86(2.2)[a]	8.85(2.1)	-1.01(0.3)	-1.01(0.4)	0.64(0.1)	0.86(0.1)
Group 2 (S)	10.78(1.0)		-1.25(0.2)		0.92(0.2)	

* Significant single-subject differences between L and C forelimbs ($p<0.05$)
[a] Significant group mean differences between L and S forelimbs ($p<0.05$)

Peak braking and propulsive GRF peaks showed no group mean differences within group 1 or between groups 1 and 2 (Table 4.2.1, Figure 4.2.1).

Figure 4.2.1 – Vertical (above) and longitudinal (below) ground reaction force traces for "mean lame" (solid gray line) and "mean contralateral" (gray line with circles) forelimbs of the lame horses (group 1), and for "mean sound" (solid black line) forelimb of the control horses (group 2).

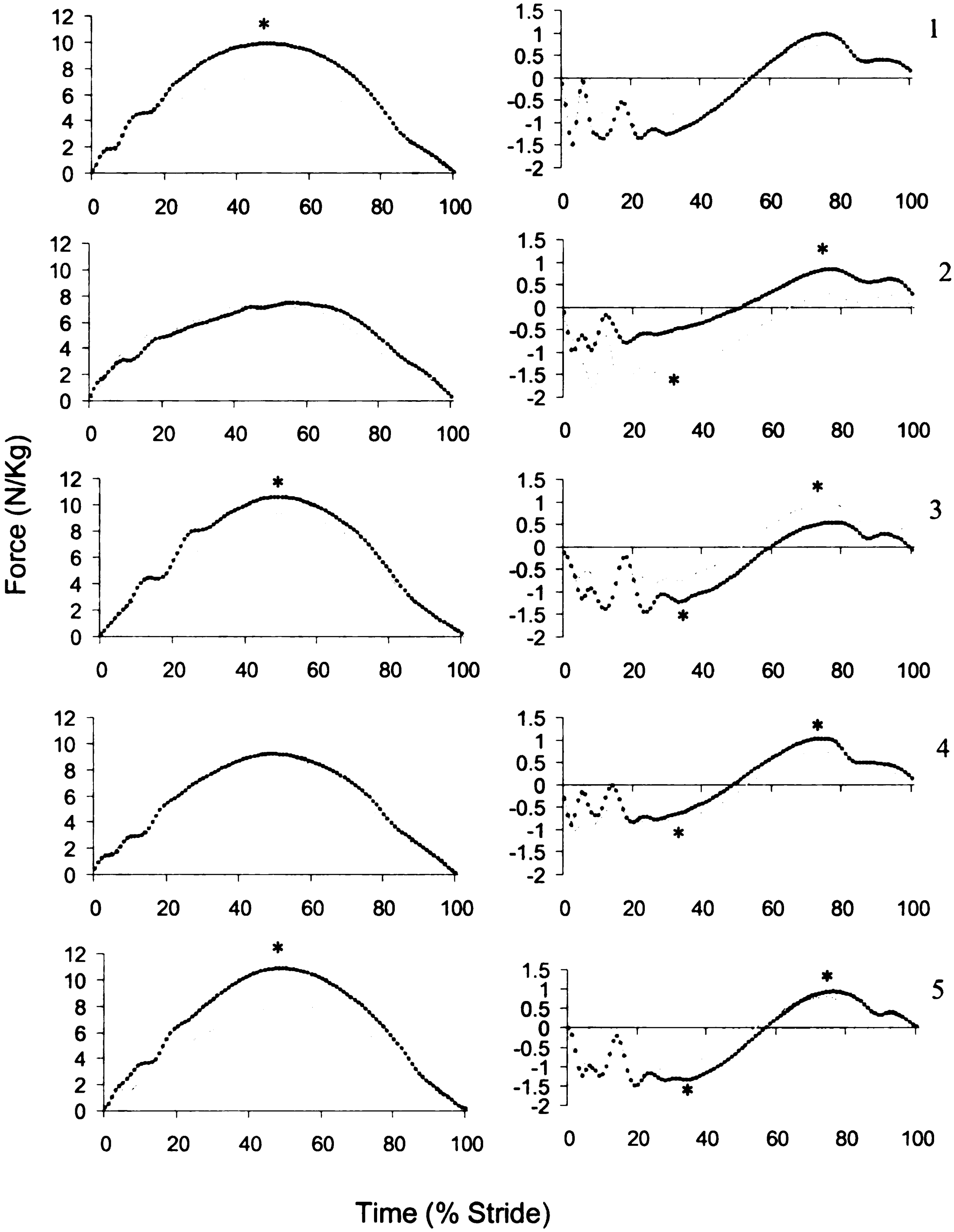


Arrows indicate the events selected for analysis (peak vertical, peak braking and peak propulsive)

* Significant group difference between "mean lame" and "mean sound" forelimbs ($p<0.05$)

Subjects 2 and 4 did not show significant single-subject differences in vertical GRF peak between lame and contralateral forelimbs (Figure 4.2.2). A high variability in the longitudinal GRF trace between subjects was observed, with no standard longitudinal GRF pattern between lame and contralateral forelimbs (Figure 4.2.2). Hence, single-subject analysis was more effective in detecting significant differences ($p<0.05$) between lame and contralateral forelimbs due to the elimination of inter-individual variability in the analytical procedure. The lame forelimb of subjects 3 and 5 demonstrated a significantly lower ($p<0.05$) braking GRF peak, while the lame forelimb of subjects 2 and 4 showed the contrary (greater braking; $p<0.05$). The longitudinal GRF showed three distinct patterns. In subjects 2 and 4 the values were higher in the lame limb, which resulted in more braking and less propulsion in the lame limb. In subject 3, the values were lower in the lame limb, which resulted in less braking and higher propulsive. In subjects 1 and 5, the lame limb showed less braking and less propulsion than the contralateral.

Figure 4.2.2 – Vertical and longitudinal ground reaction force traces for lame (solid gray line) and contralateral (gray line with circles) forelimbs of the lame horses (group 1).



* Significant single-subject differences between lame and contralateral forelimbs

In the group analysis of impulses, the "mean lame" forelimb had significantly lower ($p<0.05$) vertical impulse than the "mean sound" forelimb. No significant group differences were observed in the braking and propulsive impulses (Table 4.2.2).

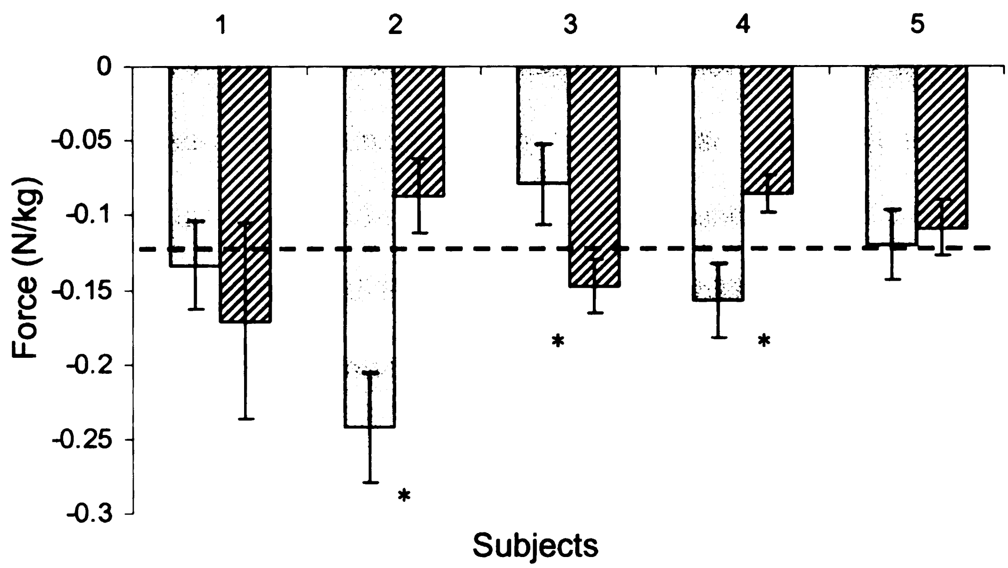
Table 4.2.2. Mean (SD) vertical, braking and propulsive impulse of lame (L) and contralateral (C) forelimbs of the lame horses (group 1), and for "mean sound" of the control horses (S; group 2).

Subject	Vertical Impulse ($Ns.kg^{-1}$)		Braking Impulse ($Ns.kg^{-1}$)		Propulsive Impulse ($Ns.kg^{-1}$)	
	L	C	L	C	L	C
1	1.68(0.0)*	2.14(0.0)	-0.13(0.0)	-0.17(0.1)	0.08(0.0)	0.09(0.0)
2	1.75(0.0)	1.67(0.1)	-0.24(0.0)*	-0.09(0.0)	0.02(0.0)*	0.09(0.0)
3	1.58(0.0)*	1.83(0.1)	-0.08(0.0)*	-0.15(0.0)	0.09(0.0)*	0.04(0.0)
4	1.85(0.0)*	1.91(0.0)	-0.16(0.0)*	-0.08(0.0)	0.04(0.0)*	0.10(0.0)
5	1.68(0.0)*	1.94(0.0)	-0.12(0.0)	-0.11(0.0)	0.07(0.0)*	0.09(0.0)
Group 1	1.70(0.1)[a]	1.89(0.2)	-0.15(0.1)	-0.12(0.1)	0.06(0.0)	0.08(0.0)
Group 2 (S)	1.92(0.1)		-0.12(0.0)		0.08(0.0)	

* Significant single-subject differences between L and C forelimbs ($p<0.05$)
[a] Significant group mean differences between L and S forelimbs ($p<0.05$)

Single subject analysis detected significant differences ($p<0.05$) in the vertical, braking and propulsive impulses between lame and contralateral forelimbs in the majority of the subjects. Subjects 1, 3, 4 and 5 showed significantly smaller ($p<0.05$) vertical impulse on the lame limb compared to the contralateral. Similarly to braking and propulsive GRF peaks, braking and propulsive impulses showed individual patterns that differed between horses (Figure 4.2.3).

Figure 4.2.3 – Braking impulse ± SD for lame (gray shading) and contralateral (striped shading) forelimbs of the lame horses (group 1).



* Significant single-subject difference between lame and contralateral forelimbs ($p<0.05$)
Dashed horizontal lines = "mean sound" forelimb

The relationship between magnitude of propulsive and braking impulses on subjects 2, 3 and 4 was similar to that of propulsive and braking GRF peaks.

4.3. BIOMECHANICAL VARIABILITY

Variability for "mean lame", "mean contralateral" and "mean sound" forelimbs was calculated by averaging the standard deviations obtained from the 5 trials of each subject. A "mean SD" was then compared between conditions (lame, contralateral and sound). Variability differences between conditions were observed for some of the kinematic and GRF variables measured. Overall, the sound condition demonstrated significantly greater ($p<0.05$) biomechanical variability than the lame condition. For instance, variability of the maximum fetlock joint extension for the lame horses ("mean SD lame" and "mean SD contralateral") forelimbs was significantly smaller ($p<0.05$) than for the sound horses ("mean SD sound"). Lame horses also showed significantly smaller ($p<0.05$) variability in stride duration than the sound horses.

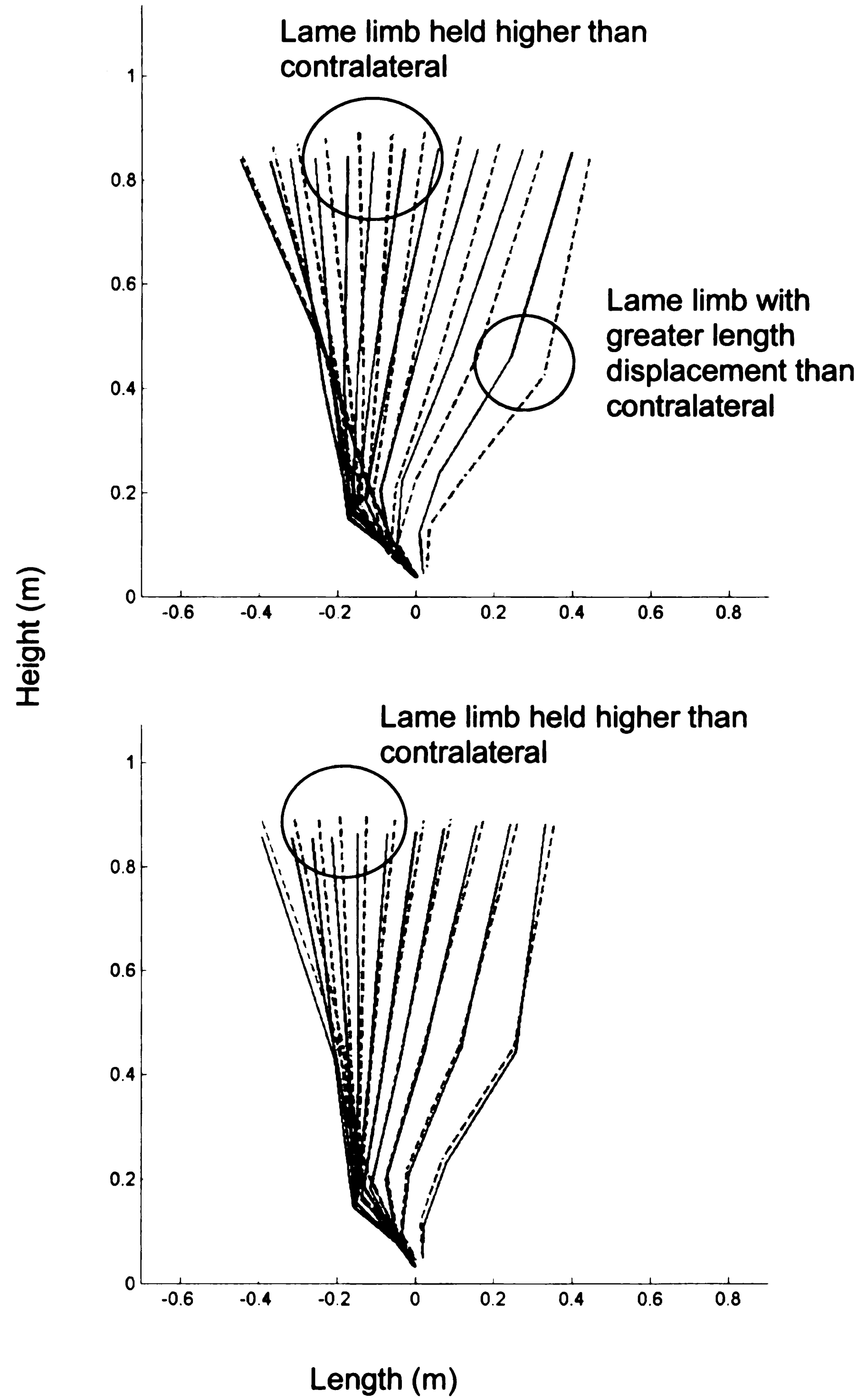
With regard to GRF variables, the variability in the propulsive GRF peak for the lame horses ("mean SD lame" and "mean SD contralateral" forelimbs) was significantly smaller ($p<0.05$) than for the sound horses ("mean SD sound" forelimb).

4.4. GRAPHICAL REPRESENTATIONS OF BIOMECHANICAL DATA

4.4.1. Kinematics

Differences in joint angle patterns were illustrated initially through the use of angle-time diagrams. Figure 4.1.1 (p. 48), which compares fetlock angles for the “mean sound”, “mean lame” and “mean contralateral” conditions, shows that there are differences throughout the stride, especially in the stance phase, when the maximum extension angle of the “mean lame” forelimb was significantly smaller ($p<0.05$) than the “mean sound”. Analysis of kinegrams from individual subjects provides an impression of the movement pattern of the entire limb and the coordination between the joints. In addition to highlighting differences in the movement patterns, kinegrams show overall differences in maximum height and length displacement of the forelimbs during the stance phase, that were quantified by including a numerical scale on the y and x axes. For instance, subject 1 held the lame forelimb higher (greater maximum height) and had a greater length displacement in the lame forelimb during stance phase than in the contralateral forelimb (Figure 4.4.1.1). Although some horses showed similar length displacement between the forelimbs (e.g. subject 3), the lame forelimb could still be identified due to the differences in maximum height of the elbow marker between lame and contralateral forelimbs, where the lame forelimb was held higher than the contralateral, especially at the beginning of stance phase (Figure 4.4.1.1).

Figure 4.4.1.1 – Kinegram of lame (dashed gray line) and contralateral (solid black line) forelimbs of subject 1 (above) and subject 3(below).

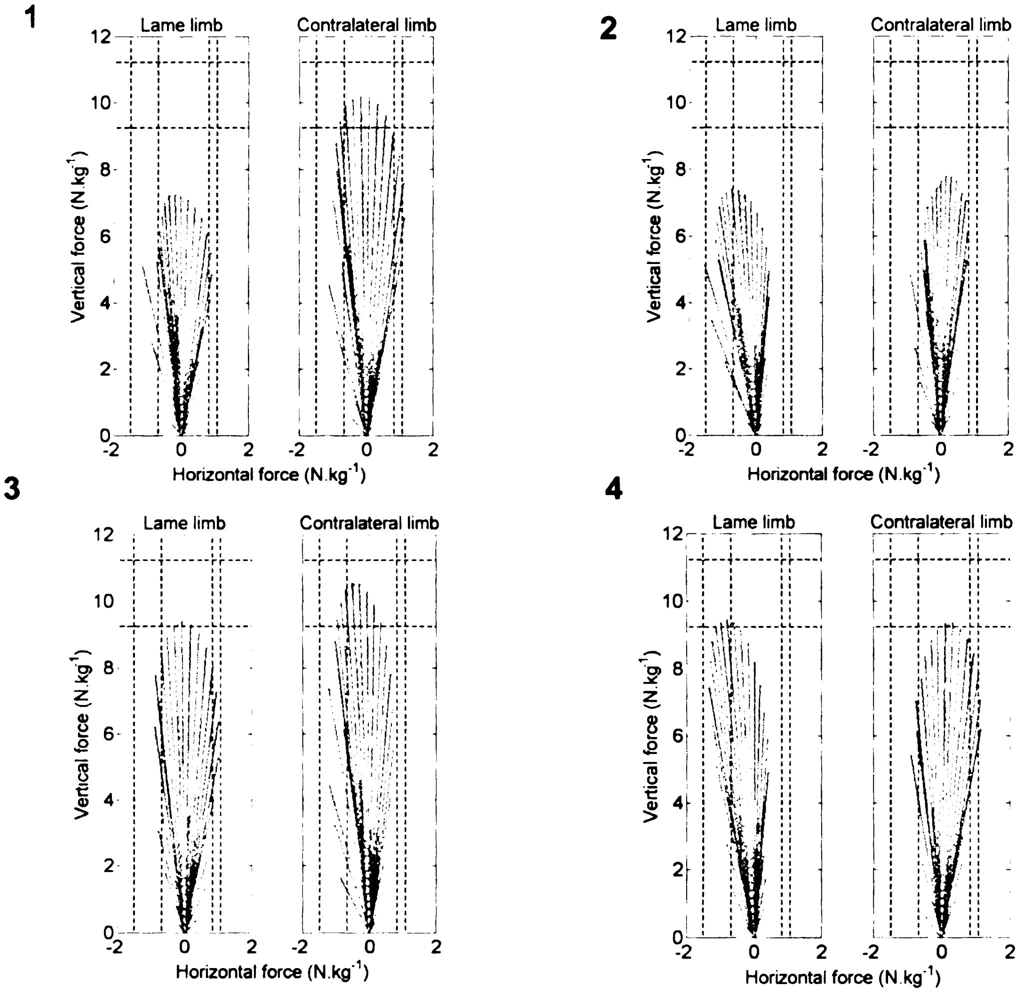


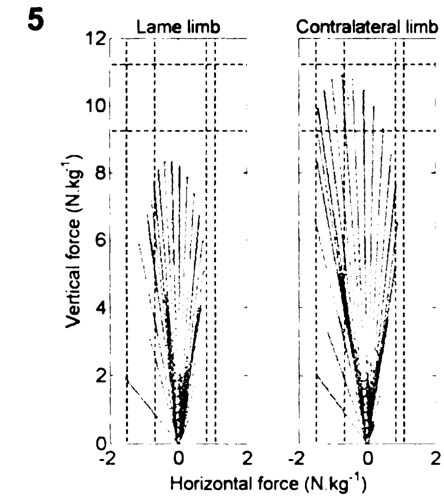
4.4.2. Ground reaction forces

Vertical force-time diagrams allowed easy recognition of the lame forelimb in subjects 1, 3 and 5, but not in subjects 2 and 4 (see section 4.2; Figure 4.2.2). Differences in braking and propulsive longitudinal GRFs were observed between lame and contralateral limbs, but the differences were not consistent between horses, making it difficult to determine which was the lame forelimb (see section 4.2; Figure 4.2.2).

Force vector diagrams allowed a more detailed visualization of differences between lame and contralateral forelimbs in vertical, braking and propulsive GRFs simultaneously (Figure 4.4.2.1). Inclusion of the SD for peak vertical, braking and propulsive forces for sound horses, which are shown as dashed lines on the force vector diagrams, facilitated the detection of lameness. The smaller peak vertical force in the lame forelimb compared to the contralateral one, which had been observed with the force-time diagram, was clearly identified with the force vector diagrams. Even when there was no difference in peak vertical force between lame and contralateral forelimbs (subjects 2 and 4), the longitudinal GRF, especially its braking component, showed a distinct difference between lame and contralateral forelimbs. In these horses, the force vectors leaned to the left indicating a larger braking force in the first-half of the stance phase. Moreover, the propulsion vectors for the lame forelimb were visibly lower than the contralateral forelimb, and did not reach the expected sound forelimb range (SD for peak propulsive force of group 1) represented by the vertical dashed lines on the right side of the force vectors. The time of mid stance of the lame limb, shown by the dashed line in between the solid force vector lines, also leaned noticeably towards the left (braking direction) compared to the contralateral forelimb.

Figure 4.4.2.1 – Force vector diagrams of GRFs from lame and contralateral forelimbs of the lame horses (group 1).





Sequential GRF vectors (every 4% of stance phase) form a fan-shaped profile. 50% time is indicated by a dashed line between vectors; SD from sound forelimbs is shown at the top of the graph for the vertical GRF, at the left of the graph for the braking GRF and at the right of the graph for propulsive GRF.

CHAPTER 5

DISCUSSION

Muskuloskeletal injuries are the most common condition afflicting racehorses (Rossdale *et al.*, 1985) and the most common reason that horses in training failed to race (Jeffcott *et al.*, 1982; Rossdale *et al.*, 1985). Horses often manifest musculoskeletal injury by changing the movement and loading profile of the limbs, a condition called lameness (Morris *et al.*, 1987). Assessment of locomotor pattern is usually based on subjective measurements gathered by the human eye with the images being processed by the human brain (Schamhardt *et al.*, 1993). Although the eyes of an experienced clinician are the most convenient diagnostic method for lameness (Perry, 1992), this subjective assessment can produce misleading judgments (Leach, 1987; Ratzlaff, 1989). Two complementary biomechanical approaches can objectively measure gait in humans and animals: kinematics and kinetics. Kinematics provides information about the geometry of motion, such as joint angular patterns, and kinetics describes the external and internal forces, such as ground reaction forces and joint torques respectively (Leach & Crawford, 1983; Galisteo *et al.*, 1997; Barrey, 1999; Nigg, 1999).

Joint angular patterns are an important indicator of physiologic and locomotor capacity (Back *et al.*, 1994; Holmstrom *et al.*, 1994). Joint angular patterns change with induced lameness (Buchner *et al.*, 1996; Keegan *et al.*, 1997), where reduction in the maximum extension of the fetlock joint has been described as a consistent finding in lameness models, such as induced carpal lameness (Back *et al.*, 1993), sole pressure-induced lameness (Buchner *et al.*, 1996) and lameness by induced superficial digital flexor tendinitis (Clayton *et al.*, 2000). The fetlock joint extends during weight acceptance then flexes as the limb pushes off the ground. The lame horses in this study showed a reduction in maximum extension of the fetlock joint, with the lame forelimb ("mean lame") being 19° less extended than the sound forelimb ("mean sound"). This is typical of a supporting limb lameness, in which the horse reduces the load on the painful limb, with a corresponding reduction in the ground reaction forces (Buchner *et al.*, 1996; Buchner, 2001). The fetlock joint angle-time curve during the stance phase has been reported to resemble the vertical ground reaction force pattern in both lame (Buchner *et al.*, 1996) and sound conditions (Riemersma *et al.*, 1988; Ratzlaff *et al.*, 1990). This relationship between vertical GRF and fetlock extension was apparent in this study in which a decrease in fetlock maximum extension of the "mean lame" forelimb was associated with a significant reduction in vertical GRF peak (3 N/kg lower vertical GRF peak than "mean sound"; $p<0.05$). As suggested by Back *et al.* (1993), the vertical GRF represents a supporting limb component of lameness, which was also evident in this study.

A reduction in maximum flexion of the coffin joint has also been associated with induced supporting limb lameness (Buchner *et al.*, 1996). However, no significant group mean differences in maximum coffin flexion were observed in this study. This lack of change in coffin flexion could be due to the high variability in coffin joint angular patterns between horses, which may have been a consequence of the different injury types and severities. In addition, previous studies describe the coffin joint as having one of the highest inter-individual variabilities (Deguerce *et al.*, 1997). Moreover, age (Galisteo *et al.*, 2001) and conformation (Deguerce *et al.*, 1997; Butcher *et al.*, 2002) have also been shown to increase inter-individual variability of kinematic measures. For instance, 2 year-old Thoroughbreds have been shown to have a quicker rate of fetlock joint dorsi-flexion compared to older Thoroughbreds (3, 4 and 5 year-old) (Butcher *et al.*, 2002). Even though no studies have been performed regarding an older population of horses, this study showed no apparent reduction in fetlock range of motion with increasing age in the control group (age = 12 ± 5.4), thus age was not considered a confounding variable in this study. Although differences in conformation between the subjects and the control group (2 Warmbloods and 3 Thoroughbreds) could have affected the analysis of kinematic variables, the data were found to be normally distributed with homogeneous variance, thus discounting this as a confounding effect and not disputing the statistical findings.

Findings regarding a decrease in carpal flexion have been controversial. Maximum flexion of the carpus has been described to decrease with induced carpal lameness and with naturally occurring navicular disease (Back *et al.*, 1993; Keegan *et al.*, 1997), but no changes were detected with sole pressure-induced forelimb lameness (Buchner *et al.*, 1996). As found by Buchner *et al.*

(1996), maximum carpal flexion remained unchanged with lameness in this study.

Single-subject analysis of joint angular patterns was more powerful than group analysis in detecting intra-individual differences between lame and contralateral forelimbs due to the abolishment of the effects of individual variation on the statistical analysis. The amount of reduction in fetlock extension in the lame limb varied between subjects and did not necessarily resemble the pattern of the vertical GRF contradicting Buchner *et al.* (1996). For instance, subject 4 demonstrated a remarkable reduction in fetlock extension (26°) on the lame limb, but the vertical GRF peaks for both lame and contralateral forelimbs were within normal limits (chapter 4, Figure 4.4.2.1.). Single-subject analysis was also able to detect angular changes in maximum extension of the coffin joint between lame and contralateral forelimbs, in particular the unexpected increase in maximum extension of the coffin joint manifested by subjects 1, 2, 4 and 5. Single-subject differences in coffin flexion were not found consistently, but there was an overall trend for maximum coffin flexion to increase in the lame limb, which was also an unexpected finding. This overall increase in angular motion of the coffin joint might be specific to fetlock joint injury; however, further studies need to be developed to investigate this hypothesis. In regard to the carpal joint, single-subject differences in maximum extension and flexion between lame and contralateral forelimbs were also diverse, with no consistent change shown by the lame limb.

The longer stance phase duration shown by the lame horses in both lame and contralateral forelimbs in comparison to the sound horses was previously reported in horses with sole pressure-induced lameness (Buchner *et al.*, 1996; Galisteo *et al.*, 1997; Keegan *et al.*, 2000), and in a single horse with chronic sesamoiditis (van Weeren *et al.*, 1993). The increase in stance duration has been suggested as a means of reducing the peak vertical force by distributing the force over a longer duration (Galisteo *et al.*, 1997; Buchner *et al.*, 1996; Keegan *et al.*, 2000). Stance duration is dependent on speed, and if not controlled, speed of the horse may voluntarily decrease with lameness (Riemersma *et al.*, 1988). In this study, trotting speed was controlled (3.0 to 3.3 $m.s^{-1}$) and an increase in stance duration was considered to be an indicator of supporting lameness of moderate degree. Besides the longer stance phase found in the lame horses, stride length was significantly reduced compared to the sound horses (2.13 m against 2.28 m; $p<0.05$), which supported the findings from induced supporting limb lameness models (Back *et al.*, 1993; Deuel *et al.*, 1995; Buchner *et al.*, 1995; Galisteo *et al.*, 1997).

In regard to the ground reaction forces, the reduction in the vertical GRF peak in the lame forelimb has been associated with a decrease in the duration of the aerial phase of the stride (Morris & Seeherman, 1987). This reduced aerial phase in a smaller vertical displacement of the center of mass cause a decrease in vertical GRF peak. Analysis of longitudinal GRFs provided complementary information for the identification of the lame limb. A reduction in the braking GRF peak has also been related to lameness and attributed to the inability of the horse to decelerate the lame limb (Morris & Seeherman, 1987). In contradiction to previous findings, group analysis did not demonstrate a decrease in braking GRF peak in the lame condition compared to the sound condition. Instead, the pattern of braking and propulsive GRF peaks showed no standard pattern between subjects.

The lack of single-subject differences in vertical GRF peak between lame and contralateral forelimbs on subjects 2 and 4 was unexpected and might be indicative of a lesser severity of lameness, bilateral lameness, or even a different mechanism of redistribution of ground reaction forces between the limbs. Hence, the use of vertical GRF peak as a supporting limb component of lameness, as suggested by Back *et al.* (1993), may be misleading if used in isolation to distinguish between lame and contralateral forelimbs, as described in previous studies (Williams *et al.*, 1999). Single-subject analysis was more powerful than the group analysis in detecting differences in longitudinal GRF and impulse between lame and contralateral forelimbs due to the elimination of the effects of individual variation in the statistical analysis. The patterns of longitudinal GRF between lame and contralateral limbs were diverse. The significant decrease ($p<0.05$) in braking GRF peak observed in the lame forelimb of subjects 3 and 5 was an expected finding and has been related to the inability of the limb to decelerate (Morris & Seeherman, 1987). In humans, a protective posturing to protect joint structures has been described as a physiological reaction to pain. As a result of this protective posturing, muscle atrophy may occur (Perry, 1992). In horses with lameness, this protective posturing may also take place causing muscle atrophy and consequent muscle weakness leading to the inability of the horse to decelerate the lame limb.

Even though subjects 3 and 5 showed similar pattern of braking force in their lame limb, the propulsive component of their longitudinal force was different, showing an increase in the lame limb of subject 3, and a decrease in the lame limb of subject 5. The increased propulsive force ($p<0.05$) in the lame limb of subject 3 was unexpected and may be due to the horse's effort to maintain a constant body velocity. Supporting the individual variation in longitudinal GRF, the braking force of subjects 2 and 4 was unexpectedly increased in the lame limb, contrary to the pattern observed in subjects 3 and 5. This greater braking force may be due to either a variation in the severity of lameness, or perhaps a different compensatory mechanism of adaptation to lameness. Indeed, in addition to the unusual increase in braking force, the lame forelimb of subjects 2 and 4 also showed a remarkable decrease in propulsive GRF peak. Therefore, the lame limb was decelerating effectively but it was unable to push the lame limb off the ground effectively. This phenomenon may be associated with the type of injury to the fetlock joint. The fetlock joint is known to be the main site for elastic energy storage and release during the stance phase (Clayton *et al.*, 1998). As the limb is loaded in early stance, the fetlock joint extends, and stretches the suspensory ligament, superficial and deep digital flexor tendons, and their respective accessory ligaments. Elastic energy is stored during loading and is later released as the limb is unloaded, thereby conserving energy. Horses with supporting limb lameness may have the loading phase of the limb compromised; therefore, the storage of elastic energy is affected. Although subjects 2 and 4 did not have significant differences in vertical GRF peak between lame and contralateral forelimbs, the vertical force was abnormally low in both limbs. The resulting decrease in elastic energy release may have caused a reduction in force available for push off, leading to a reduced propulsive GRF peak at the end of the stance phase.

Interestingly, the variability of some kinematic (maximum fetlock extension and stride duration) and GRF (propulsive GRF peak) variables was much lower in the lame condition compared to the sound condition. Peham *et al.* (2001) suggested that horses with orthopedic pain keep stride variability low to optimize compensatory mechanisms to reduce pain in the affected limb. Variability is said to offer flexibility to adapt to perturbations (Holt *et al.*, 1995) and is essential to the changing coordination patterns during locomotion (van Emmerick *et al.*, 1999). In humans, van Emmerik *et al.* (1999) demonstrated that individuals with patellofemoral pain displayed reduced coordination variability among joint couplings of the painful limb, with the individuals avoiding painful coordination patterns (Heiderscheit *et al.*, 2002). Force variability has also been suggested to increase as the level of force produced increases (Jenkins, 1947; Noble & Bahrick, 1956; Provins, 1957), so the decrease in variability of the propulsive GRF peak could be explained by the overall reduction of GRF manifested by the lame horses. The reduced variability in some of the kinematic and GRF measures supports previous studies and suggests the use of movement variability as a discriminating measure and possible clinical tool.

Illustration of kinematic measures, such as joint angular patterns, further detection of the lame limb was achieved with the use of angle-time diagrams. The stance phase is subjected to coordination changes with supporting limb lameness (Stashak, 2002), thus the use of kinegrams from the stance phase represented the motion of the entire limb and highlighted asymmetries and changes in coordination between the limbs. As suggested by Back *et al.* (1995), the association of joint angle-time diagrams with the movement of the entire limb may facilitate the interpretation of kinematics. This study supports the fact that graphical displays of kinematic data enhance understanding and suggests that the incorporation of kinegrams from the stance phase facilitates the identification of lameness. In regard to ground reaction forces, this study suggests that in addition to analysis of the vertical GRF pattern, the longitudinal GRF should also be used for identification of gait abnormalities. The lack of significant differences in the peak vertical GRF between lame and contralateral forelimbs in subjects 2 and 4 supported the findings from previous studies showing that asymmetry in peak vertical force may be misleading if used in isolation to distinguish between normal and abnormal gait patterns (Merkens & Schamhardt, 1988; Williams *et al.*, 1999). Individual responses in ground reaction forces, especially in the braking component of the longitudinal GRF, made it difficult to show statistical significance between limbs; hence in addition to the force-time diagrams, a simpler method to measure lameness is required.

The use of force vector diagrams to compare lame and contralateral limbs proved useful identifying the lame limb. Vector diagrams have been used in human gait analysis to illustrate pathological gait patterns (Rozendal *et al.*, 1985; Khodadadeh, 1988; Baumann *et al.*, 1992), but their use in horses as a potential diagnostic tool for lameness evaluation has been limited (Merkens *et al.*, 1985; Merkens *et al.*, 1988). Force vector diagrams are beneficial as they enable more than one variable (i.e. peak vertical, braking and propulsive GRFs) of both limbs to be observed and analyzed simultaneously. The inclusion of lines illustrating the SD for the peak forces based on data from sound horses was also helpful for detecting abnormal forces in the contralateral limb. Changes in the movement pattern in response to pain have been described to redistribute loads through other joints in the body and boost the development of secondary injuries (Whiting & Zernicke, 1998). Detection of abnormal forces in the contralateral limb is imperative because it could contribute to the development of secondary injuries. Similar to what was demonstrated in previous studies (Schamhardt *et al.*, 1993; Merkens *et al.*, 1993), force vector diagrams facilitated evaluation of left versus right symmetry, or asymmetry of specific points on the force time curve. Indeed, these diagrams were easier to understand than more complex approaches, such as the use of principal component analysis (Williams *et al.*, 1999). Left versus right symmetry of GRFs in equine locomotion is relevant to athletic ability (Dow *et al.*, 1992), and identification of force vector asymmetries consistent with pathological gait characteristics might assist practitioners to establish a diagnosis and prognosis, and to assess the therapeutic response.

CHAPTER 6

CONCLUSIONS

Refinement of the diagnosis of pathological gaits, study of the etiology of muskuloskeletal disorders and evaluation of treatment may be improved through objective quantitative analyses (Keg *et al.*, 1994). This study has demonstrated that:

- Kinematic measurements can detect gait abnormalities in horses, with fetlock joint maximum extension, stance phase duration and stride length being the main indicators of fetlock joint lameness.
- Vertical ground reaction forces tend to show an overall reduction in the lame limb.
- Longitudinal GRFs are highly variable between horses even when the etiology of lameness is similar.
- Group statistical analysis was not an effective method of characterizing lameness in horses with fetlock joint injuries due to inter-individual variation.
- Single-subject analysis offers a powerful intra-individual analytical method to determine asymmetries between lame and contralateral limbs and therefore, detecting lameness.
- Lame horses reduce their intrinsic movement variability to avoid painful coordination patterns.

- Movement variability may be used as a discriminating measure and possible clinical tool. Based on this information, clinicians can incorporate measures of movement variability to aid in the design of appropriate treatment programs directed at these deficits.
- Graphical displays such as angle-time diagrams, kinegrams, force-time diagrams and force vector diagrams facilitate the interpretation of biomechanical data and can be used as simple tools to quantify lameness objectively.

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