DISSERTATION

COMPARING PRESSURE MEASUREMENT SYSTEMS AND A FORCE PLATFORM AS TOOLS FOR EQUINE GAIT ANALYSIS

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY VALERIE PERINO ENTITLED: COMPARING PRESSURE MEASUREMENT SYSTEMS AND A FORCE PLATFORM AS TOOLS FOR EQUINE GAIT ANALYSIS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

COMPARING PRESSURE MEASUREMENT SYSTEMS AND A FORCE PLATFORM AS TOOLS FOR EQUINE GAIT ANALYSIS

Objective assessment of lameness in the horse has been well established through testing with force platforms. The force platform measures ground reaction forces in three orthogonal directions: mediolateral (F_x), craniocaudal (F_y) and vertical (F_z). Testing with force platforms has shown researchers that this technology is capable of providing accurate and reliable quantitative data for use in lameness assessment. However, the cost of force platform systems, setup and training as well as the lack of mobility of the systems has driven researchers to look for alternative systems which are user-friendly, less expensive and capable of field use rather than a laboratory environment.

Pressure measurement systems were designed for use in the human podiatric profession in order to provide a quick and easy method for determining vertical ground reaction forces, contact area and plantar pressures. Previous testing of the F-Mat system (Tekscan, Boston, MA) showed accurate calibration was extremely important for optimum performance and that standard sensor manufacturing caused sensors to saturate under the loads of horses therefore not providing accurate and reliable data. However, testing of the equine F-Scan system (Tekscan, Boston, MA) showed that pressure measurement systems were capable of assessing lameness in the horse on a treadmill. With careful calibration and proper design of sensors specifically for horses, tests were designed to compare the ability of the F-Mat and Equine F-Scan mobile units (a system capable of recording pressure measurements from the hooves without being connected directly to a computer) to a force platform to measure vertical ground reaction forces. Results from this study indicate that proper sensor design and calibration help the pressure systems to measure vertical ground reaction forces with values similar to a force platform. Statistical tests show the pressure systems are not as precise as the force platform for repeated measurements and the accuracy of the mobile unit can be comparable to the force platform but the F-Mat was not. This study provided proof that the equine mobile unit could quantitatively assess lameness in the field. Further development of the mobile unit will make the system easier to attach to the horse and use. Thereby providing researchers and practitioners with an alternative to the force platform than can be used in the field to provide accurate and reliable data to quantitatively assess lameness in the horse.

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CHAPTER 1

Introduction

1.1 Purpose

The purpose of the following research was to test the ability of the F-Mat and Equine F-Scan (Tekscan, Boston, MA) pressure sensitive, thin film sensor systems to accurately and precisely measure vertical ground reaction forces when compared to a force platform. The proposed research did include 1) testing the precision of the mat (F-Mat), in-shoe system (Equine F-Scan) and a force platform by taking multiple measurements with each subject and observing the coefficients of variation; 2) correlation of vertical force measurements from the force platform to the vertical force measurements from both the mat and in-shoe systems and; 3) testing for measuring agreement between the vertical force measurements from the force platform, mat and in-shoe systems. Testing of the equine F-Scan systems includes testing of a data-logging unit with a trimmable and a non-trimmable sensor.

1.2 Goals

The long-term goal was to test the accuracy and precision of the equine in-shoe system, a user-friendly, relatively inexpensive pressure measurement system to measure vertical ground reaction forces.

1.3 Statement of Hypothesis

The hypothesis to be tested states: Using the F-Mat, Equine F-Scan and force platform systems, vertical ground reaction forces will precisely be measured enabling the accurate objective assessment of lameness.

1.4 Specific Aims

1.4.1 F-Mat System – Testing the Accuracy of the Mat vs. a Force Platform (Chapter 2)

(1) To test the accuracy of the F-Mat system compared to a force platform.

  a. **Hypothesis** – The F-Mat system will record measurements of vertical force and these measurements will be accurate when compared to vertical force measurements taken simultaneously on a force platform.

1.4.2 F-Mat System – Testing environmental factors that affect precision of pressure measurement systems (Chapter 2)

(1) To determine the effects of multiple rates of trotting velocity on vertical ground reaction forces.

  a. **Hypothesis** – Trotting speed will not change the ability of the pressure system to objectively assess lameness.

(2) To determine the effects of different calibration loads on vertical ground reaction force measurements.

a. **Hypothesis** – The F-Mat system will record vertical force measurements while calibrated with two different loads and this will not affect the overall vertical force measurements.

1.4.3 Fuji Film – Designing sensors for the Equine F-Scan system (Chapter 3)

(1) To determine peak pressures reached by a horse while trotting in order to produce thin film sensors capable of measuring peak pressures and vertical ground reaction forces without becoming saturated.

a. **Hypothesis** – The Fuji film will measure peak contact pressures over multiple exposures and will provide precise enough measurements to estimate peak contact pressure of a horse during trotting.

1.4.4 Equine F-Scan system with non-trimmable sensors – In-shoe measurements (Chapter 4)

(1) To determine the ability of the equine F-Scan system with non-trimmable sensors to accurately and precisely measure vertical ground reaction forces.

a. **Hypothesis** – The equine F-Scan system with non-trimmable sensors, the F-Mat and a force platform will record measurements of vertical force that will be precise with little variability.

b. **Hypothesis** – The equine F-Scan system with non-trimmable sensors and the F-Mat will accurately record vertical force measurements when compared to the measurements from a force platform.

1.4.5 Equine F-Scan System with trimmable sensors – In-shoe sensors for vertical force measurements (Chapter 5)

(1) To determine the ability of the equine F-Scan system with trimmable in-shoe sensors to accurately and precisely measure vertical ground reaction forces.

  a. **Hypothesis** – The equine F-Scan system- with trimmable sensors, the F-Mat and a force platform will record measurements of vertical force that will be precise with little variability.

  b. **Hypothesis** – The equine F-Scan system with trimmable sensors and the F-Mat will accurately record vertical force measurements when compared to the measurements from a force platform.

(2) To correlate vertical force measurements from the equine F-Scan system with trimmable sensors to force platform measurements to establish the accuracy of the equine F-Scan system.

  a. **Hypothesis** – The vertical force measurements from the equine F-Scan system will show a correlation with vertical force measurements from the force platform.

(3) To show measurement agreement between the vertical force measurements from the equine F-Scan system and the measurements from the force platform.

a. **Hypothesis** – The differences in measurements between the equine F-Scan system and force platform will allow investigators to assess agreement between devices.

1.5 Background and Significance

1.5.1 Importance of Lameness

Lameness has been defined by the American Association of Equine Practitioners (AAEP) as a deviation from the normal gait or posture due to pain or mechanical dysfunction [2]. Using this definition, clinicians around the world have recognized musculoskeletal injuries as the number one reason equine athletes have been forced to interrupt or quit their athletic careers [3, 4]. In the early 1980s, the British Equine Veterinary Association conducted a survey which concluded that from the horses surveyed at one racetrack, 53% of the total number of animals experienced some period of lameness and of those cases, 20% of the individuals suffered injuries which prevented further racing [5]. In a more recent survey by the United States Department of Agriculture, National Animal Health Monitoring System it was reported that one-half of U.S. horse operations reported having at least one horse with a lameness in the past year [6]. The expense of lameness from this survey was estimated to be between $678 million to $1 billion dollars per year in 1998 [6]. In addition the USDA Census of agriculture reported an increase from 2 million equine (horses, ponies, mules, burros and donkeys) in the U.S. in 1992 to 5.25 million in 2002 [7]. The increase in the total number of horses in the U.S. and throughout the world has made lameness evaluation a major part of clinical practices. Because of the difficulty in assessing lameness, researchers have been trying for many years to integrate modern·technology into gait studies [8]. Further extension of the use of these technologies into the clinical field requires well tested protocols and simplified methodology with precise identification of all important parameters for analysis [9].

1.5.2 Gait Analysis

Humans have been observing conformation and movement in horses dating back to 445 BC [10]. The physical appearance of the horse dictated primarily by bone and muscle structures is an important part of identifying potential problem areas upon physical examination. Movement of the horse is defined by travel, the flight of the hoof in relation to other limbs, and action, which takes into account joint flexion, stride length and suspension. Travel can be viewed from the front or rear of the horse while action is assessed from a side view [11].

Most often lameness is identified on the observation of asymmetric movements of limbs associated with normally symmetric gaits such as the trot or pace [10, 12]. The trot is a two-beat diagonal gait with the following sequence: right front and left hind rise and fall together alternately with the left front, right hind pair [11].

Observers also look at the phases of the stride for abnormalities. The horse's stride is broken into five phases: landing, loading, stance, break over and swing. During landing, the hoof touches the ground and begins to receive weight. The body moves forward and the horse's center of gravity passes over the hoof during loading. In the stance phase, the horse's center of gravity moves past the hoof, the pastern straightens and the limb begins pushing off the ground. Break over is the phase when the hoof leaves the ground and moves into the swing phase which moves the limb through the air and gets ready for landing [13]. Observation of the horse through movement allows clinicians to watch for abnormalities and assess degrees of lameness.

1.5.2.1 Subjective Lameness Evaluations

Subjective lameness evaluation allows clinicians to observe horses moving to determine a starting point for further testing or rehabilitation of animals moving in an abnormal gait. Based on the definition of lameness as previously stated, the AAEP adopted a scale for classifying lameness. The classification system is defined as follows: A grade 1 defines movement by a horse in which any abnormal movement is difficult to observe, and not consistently apparent under most circumstances (i.e. circling, inclines, hard surfaces, etc.). A grade 2 is difficult to see at a walk or trotting in a straight line but is consistently apparent while circling on inclines or hard surfaces. A grade 3 is consistently observable at a trot under all circumstances. A grade 4 is an obvious lameness with marked nodding, hitching or shortened stride. A grade 5 shows minimal weight bearing in motion or at rest, and possibly an inability to move [14]. Observation of animals moving allows clinicians to evaluate the movement of the horse and subjectively score the movement based on the AAEP guidelines.

The ability of the human eye to detect changes in gait is limited by the temporal resolution of the eye [12]. Clinicians can often become very skillful in detecting the slightest changes in gait [12]. However, they are incapable of detecting changes that occur in less than a tenth of a second [12]. Traditionally, clinicians have assessed the degree of lameness observable and then performed further testing to localize the source of the lameness. In order to do this, clinicians will accentuate the severity of the lameness by physical manipulation, such as flexion tests and hoof testing. The lameness is then reduced using diagnostic blocks. The lameness can be further characterized by radiography, ultrasonography, nuclear scintigraphy, CT, MRI and arthroscopy [4, 15]. Subjective evaluation is helpful in diagnosing and monitoring changes in gait patterns. The use of the AAEP classification system helps to standardize observations between clinicians. However, the largest drawback of subjective evaluation is the lack of objective output providing continuous data. Also, the accuracy and precision of the diagnosis is dependant on the experience and opinion of the clinician.

The ability of the human eye to detect changes in gait is limited by the temporal resolution of the eye, which cannot distinguish events occurring in less than 0.1 second [16]. Due to this, a subtle lameness may not always be diagnosed by subjective evaluation because subtle lamenesses are recognized by the AAEP as a grade 1 or 2 and are not consistently observable under all testing conditions. The difficulty of identifying subtle lameness is particularly true in cases in which the lameness is evident only during speed, or lameness is due to lesions at multiple locations. In these cases subjective evaluation can be supplemented with quantitative measures of locomotion [4].

A visual analogue scale (VAS) is also available for subjective assessment of lameness. The VAS uses a 100-millimeter horizontal line with vertical lines at either end. One end is labeled 'sound' and the other is labeled 'cannot be more lame'. The VAS system is more sensitive than the numerical rating scale when used for assessment of lameness in sheep and has been used extensively in humans to subjectively measure pain or relief in humans [17]. It is believed that because the VAS system allows the observer to consider more than one factor at a time, this might make the VAS a system for measurement of lameness with increased sensitivity [17]. In this particular study, *Welsh* and colleagues looked at sheep and compared the VAS scale to a numerical rating scale (NRS) [17]. Two observers made assessments of 45 sheep using the VAS and NRS scales. From these assessments it was determined that the reproducibility of the VAS varies along the line, with the greatest reproducibility along the edges and the center. From this, investigators determined that reproducibility and repeatability of results varies the most when the animals are perceived to be moderately lame [17]. The region +/- 20-mm from the center point causes the most difficulty with reproducibility and repeatability because of the wide variability in estimates of moderate lameness [17]. In human cases, the patients scored their own pain [17].

1.5.2.2Objective Lameness Evaluations

Integration of gait analysis into clinical settings is a common goal of many research groups. Analysis of the motion of horses was first undertaken in the 1870s by Marey who studied the timing of each gait. Later, Muybridge used a series of cameras to analyze the horse's locomotion [10]. Research using gait analysis to study locomotion continued and has made great progress in the last 30 years [10]. Researchers have used several methods of gait analysis to determine lameness, specifically kinematic and kinetic methods.

1.5.2.2.1 Kinematic Evaluation

Kinematic analysis quantifies the features of gait that are assessed qualitatively during a clinical examination [12]. Kinematics is the study of changes of position of the body segments in space during a specified time [10]. The motions are described quantitatively by linear and angular variables that relate time, velocity, displacement and acceleration [10]. Methods of kinematic analysis include high-speed cinematography, videography, optoelectronics and electrogoniometry [10, 12, 18].

Videography is a popular method of kinematic analysis [12]. The modern approach to videography uses markers glued on the skin which are filmed by cinematographic or video cameras [10, 12]. After video recording the animal's movements, data must be digitized, transformed, smoothed and normalized before statistical analysis [12].

Analyses may be performed in two or three dimensions [12]. Because horses limbs move in a sagittal plane, most information is found in the 2-D view [12]. Timing variables describe the timing and sequence of limb placements. Each stride has a stance phase, when the hoof is in contact with the ground and a swing phase, when it swings forward in preparation for the next stance phase. Step duration of forelimb and hindlimb pairs describes the impact of the left and right limbs. Breakover is the period between lift off of the heels and lift off of the toe. The duration of the stance phase is often effected by lameness. In lame horses the sequence of limb placements and lift-offs may be different on the left and right sides. Distance and angular data describe the spatial relationship of the body parts. Stride length is approximated by measuring the distance between successive placements of the same limb [16]. All of this data is only as accurate and reliable as the user of the system makes it by proper setup, data acquisition, data analysis and statistical analysis [12].

Researchers have taken note of visual cues used by experienced clinicians to aid subjective assessments of lameness. Such parameters include head movement, characteristics of stride length, duration of weight bearing, limb carriage and joint movement [19]. Videographic assessment of horses trotting on a treadmill have enabled Keegan, et al. to attempt to correlate subjective lameness scores with certain kinematic variables [19]. The kinematic variables thought to be most useful to investigators were variables for stride displacement, joint angle of the carpus and fetlock from 2-dimensional position and stride temporal evaluations from 3-dimensional position data. Correlations were noted between clinicians change in subjective score to the mean value for minimum poll height and duration between maximum hoof height and midswing during a stride [19]. Minimum poll height difference was positively correlated with change in lameness score, indicating an improvement in a right limb lameness correlated with a decrease in asymmetry of vertical head movement between right and left forelimb stance phases. In addition, maximum hoof height and midswing during a stride was positively correlated with change in lameness score, indicating an improvement in a right forelimb lameness correlated with maximum hoof height that was detected closer to midswing [19]. Keegan, et al. concluded that mild lameness may be difficult to evaluate during treadmill locomotion and therefore emphasizes a need for the use of more objective measures for quantifying lameness [19]. Other investigators have also used automated optoelectronic systems to objectively quantify lameness. Correlations between clinicians' subjective lameness scores and maximal carpal flexion, maximum fetlock extension and stride length have been noted by Back, et al as well [20].

Kinematic variables such as stride length, stride duration, diagonal advanced placement, fetlock hyperextension and others were studied by Buchner et al. [21]. These variables were shown to be difficult parameters to assess mild bilateral lameness. Changes between sound and bilaterally lame measurements in the kinematic variables with variation in fetlock hyperextension only differed by 2 degrees, variation in diagonal advanced placement differed by 10ms, stride length differed by 0.03m, stride duration differed by 0.9% in the forelimb and 0.2% in the hindlimb [21]. The small and symmetric changes made diagnosis of bilateral lameness difficult, however changes in fetlock hyperextension and diagonal advanced placement were shown to be parameters that could be used for early detection of bilateral lameness [21].

Investigators took kinematic gait analysis one-step further using vertical motion of the head. Using a fourier series representative of the motion signal from digitized video of horses trotting on a treadmill, Peham et al. compared the fourier analysis with subjective grading of a front limb lameness [22]. Vertical head motion can be separated into 2 frequencies. In sound horses, the head is lowered similarly in both front limbs during the stance phase; therefore the head frequency is twice the frequency of the motion cycle. If there is a supporting limb lameness, additional head nodding occurs during the stance phase and is seen at the same frequency as the motion cycle. Assignment of lameness was done using the motion of the hoof. If the fundamental wave of the head was in phase with the fundamental wave of the left forelimb, the horse showed a supporting limb lameness of the right forelimb. If the waves were out of phase, the horse showed a supporting limb lameness of the left forelimb. Degrees of lameness are compared by the percent of symmetry, classifying anything less than 60% as second degree which is seen clearly as the head was lowered considerably during the stance phase of the sound leg [22]. Peham et al. also used symmetry measurement to measure hind limb lameness and found it worked there as well [23].

Accelerometers are small devices that can be attached to a limb or trunk segment to measure the acceleration of that body part. Values of angular velocity and information on position can be calculated from accelerations. Acceleration can be evaluated on one, two or three axes [18].

Accelerometers are believed to be a tool with which investigators can move away from the treadmill and still provide measurements of head and joint movement. By using a telemeterized system with 2 accelerometers, one attached to the halter on the head and one on the midline of the pelvis with 2 goniometers placed on the right forelimb and one on the right hindlimb investigators at the University of Missouri were able to take measurements on a flat asphalt surface that were comparable to readings on a treadmill that diagnosed a lameness [24].

Kinematic gait analysis has advanced over the past 30 years. Automation of optoelectronic systems has enabled researchers to digitize video data much more quickly and transformations of that data have become relatively easy. Researchers have been able to define kinematic variables from 2-dimensional and 3-dimensional analysis that will show change between a normal gait and an abnormal gait. Investigators have also realized that the combination of kinematic and kinetic measurements provides a much more powerful tool for analysis of gait. However, it should be noted that most kinematic measurements are done in a laboratory setting where cameras are set in place and animals trot or walk on treadmills because the setup of equipment elsewhere is difficult and recording data for an area larger than a treadmill requires more equipment and dedicated space.

1.5.2.2.2 Conventional Methods of Kinetic Evaluation

Kinetic motion analysis is the study of the cause of the motion, which can be explained by the force applied to the body, its dimensions and mass distribution [10]. Methods of kinetic analysis include force and pressure plates and shoes, strain gauges [10, 12, 18].

Strain gauges are a kinetic system used to assess lameness. Strain gauges measure strain, which is the amount of deformation of body tissues as a percentage of the original dimensions. A combination of three strain gauges stacked at 45-degree angles to each other form a rosette gauge capable of measuring three-dimensional strains. Strain gauges can be used as components of force plates, force shoes or independently [12]. Several types of strain gauges have been used to study tendon strains in horses [12]. Custom made mercury-in-silastic strain gauges were implanted in the right forelimb of ponies to measure strain on the superficial digital flexor tendon, deep digital flexor tendon, inferior check ligament and the suspensory ligament with different types of shoes [25]. Changes in strains were correlated to changes in torques calculated from ground reaction forces acting on the coffin joint [25].

Measurements from strain gauges can also be used to calculate stress in hard surfaces. Rosette gauges bonded to the bone surface deform with the bone surface to provide information about compressive and tensile forces [12]. On bone's surfaces it is possible to attach rosette strain gauges to measure local strains. Calculation of forces is then possible using published values of elastic moduli, shear modulus and Poisson's ratio. Strain gauges have limitations on the measurements provided. The strain data provided by each gauge is only relevant to the area of the bone where the gauge is adhered and so assumptions must be made about the properties of the bone around that area. Also, there may be some surgical affects from implantation that change the properties of the bone and surrounding tissues [26].

Strain gauges may also be bonded to the hoof capsule easily. Using two gauges placed on the toe and lateral hoof wall, hoof wall strain can be measured. From these measurements ground reaction forces can be estimated. However, due to the lack of linearity between hoof wall strain and ground reaction forces, artificial neural networks may be used to recognize the patterns produced [12]. Artificial neural networks are made up of computational cells organized in layers. The connections of layers are given different weights. As data is presented to the cells of the first layer, multiplication of each of the cells output is sent to the subsequent layers. By adjusting the weights, a network is trained to produce relationships between input and output patterns. To train a network, data is provided from hoof wall strain and ground reaction forces from a force platform. After proper training, the network is able to use one pattern to calculate the other pattern [27]. Savelberg et al. were able to calculate ground reaction forces from hoof wall strains using artificial neural networks using 2 gauges on different sites [27].

Strain gauges may be used to objectively assess lameness. However, the sensitivity of the materials used to make strain gauges makes them very fragile. Also, it is very easy to have high rates of variability in measurements due to unexpected changes or movements of the strain gauges at connection points, sometimes voiding results.

Force platforms measure the response by the surface, ground reaction force, to the subject stepping on the plate [28]. Four basic designs of force platforms have been tested. Those include: mechanical spring and pointer systems, piezoelectric crystals, linear variable differential transformers, and electrical resistance strain gauges [29].

Piezoelectric force platform systems were developed in the 1950s. This system is based on the principal that certain crystals will respond to changes in shape by the generation of an electric charge. This system has quartz crystals placed in the corners and the crystals are attached to electrodes so that as deformation of the crystals occurs, a voltage is produced that is proportional to the force applied. That output voltage is amplified, displayed and stored for mathematical analysis [29].

The orientation of the quartz crystals in the corners of the force platform allows measurement of the three orthogonal forces: mediolateral (F_x), craniocaudal (F_y), and vertical (F_z) [29]. Force platforms enable one to measure vertical and shear forces as well as the center of pressure during gait because the measurements are taken during weight bearing [28, 29].

Linear variable differential transformer force platforms use a core magnet and a series of coils in which mechanical displacement is converted into an electrical impulse. This system can measure the three orthogonal forces as well [29].

Strain gauge force plates use strain gauges to measure the stress in load cells when a load is applied. The change in electrical resistance from the gauge is proportional to the deformation of the cells when loaded. Strain gauge force platforms are durable, very sensitive and show only small variation in the force measured [12, 28, 29].

Use of the data obtained from force platform analysis is increasing in the veterinary medical research field. As the capabilities and limitations of this tool are proven, application to research is being defined [30-40]. Evaluation of data from force platform analysis is proving to be a valuable means of assessing the outcome of medical and surgical interventions in orthopedic diseases and thereby providing an objective method of quantifying treatment of orthopedic disease [40-48].

Clinical studies in human, equine and canine subjects using force platform data are becoming more numerous [33]. The use of specific data collection parameters is paramount to the collection of useful data from force platforms. The effects of nonorthopedic factors such as forward velocity, stance time, subject size, and weight on the data generated from force platform analysis are beginning to be tested [33]. For example, the forward velocity the subject moves across the force platform with may significantly affect the peak vertical and horizontal craniocaudal forces. It has been shown in human studies that peak vertical and horizontal craniocaudal forces increase significantly as a subject's forward velocity increases [49-51]. Likewise, subject velocity may also significantly influence impulses (average force applied over time). As subject velocity increases, impulses per step decrease [33]. In order to control for the influence of weight of the subject on the force platform data, investigators normalize all force related measurements by expressing force as a percentage of body mass [52].

As an example, the velocity at which the dogs travel across the force platform greatly affects the generation of ground reaction forces [30, 32, 33]. Millisecond start/interrupt timers have been used to provide accurate measurements of average speed between start and stop times and to control variations in velocity of travel by the dogs [30, 32, 36]. Stance time may be an accurate indicator of subject velocity. In walking dogs an inverse relationship was observed between stance time and peak vertical force. At a trot a direct relationship was observed between velocity and peak vertical force. This suggests that velocity and stance time are related and changes in stance time accurately reflect changes in subject velocity as well as ground reaction forces in clinically normal dogs [30, 33, 36, 43].

In addition, research that uses a comparison of sides for gait analysis of healthy and diseased limbs in one animal has potential for error. This is due to the redistribution of force and center of mass displacement resulting from the lameness. Therefore, the extent of redistribution of vertical ground reaction forces must be established so that researchers can compare normal to treated and know the trends that stance time and vertical ground reaction forces will follow [45].

For many years force platform systems were used on equine subjects without standardization in experimental protocol, data analysis and presentation of measurements making it very difficult to compare and interpret results [53]. Therefore, analysis of ground reaction force data from normal horses at a walk and trot was needed in order to compare lame horses to normal horses. By comparing force – time curves obtained from normal horses and those with injury or disease, the degree of lameness could be assessed. In order to do this, a 'standard' horse was created by averaging data obtained from a group of clinically sound animals of similar use and breed. This study tested Dutch Warmbloods at a walk and then looked at force-time curves from other studies conducted by Pratt and O'Connor (1976), Schryver (1978) and Gingerich et al (1979), which looked at force-time curves of Thoroughbreds [54-56]. Comparison of force curves from different breeds of animals showed differences in bends in the curves that support the view that force platform data should only be compared between animals of the same breed [53]. This was seen in the comparison of the force curves in which enough differences were noted between the force curves produced by Dutch Warmbloods and Thoroughbreds that the authors felt comparison of different breeds would not be a reliable method of measuring lameness [53].

To determine how force platform measurements are applicable in the evaluation of treatments of disease, quantification of limb loading patterns, as well as the comparison of limbs using shear forces must be accomplished. The symmetry between left and right fore- and hind limbs is very high in normal horses and may differ greatly in cases of lameness [52]. Complex methods of gait analysis will often include assessment of force platform measurements and kinematic data to supply an objective assessment identifying normal and diseased states.

A combination of force measurements, net joint moments, powers and energies has been used to evaluate the effect of specific lameness's on locomotion. In human subjects, joint powers and energies have been determined to be the most useful variables for assessing pathological gait [57]. By combining ground reaction forces and kinematic data for equine limbs using an inverse dynamics solution, net joint moments and joint powers can be computed [58]. A net joint moment is defined as the sum of all of the torques acting around a joint. The joint power measures the mechanical energy absorption or generation across a joint associated with the net joint moment. When the net joint moment acts in the same direction as the angular velocity of the joint, the joint power is positive and energy is generated indicating that the muscle shortens as it generates tension by a concentric contraction. The joint power is negative and energy is absorbed when the net joint moment acts in the opposite direction to the angular velocity of the joint, indicating the muscle lengthens as it generates tension by an eccentric contraction. During power absorption the muscles control or restrain joint movement in opposition to gravity or an external force [59]. The net joint moments for the forelimb have been described in trotting and walking horses [58, 60-63]. In addition, Clayton et al., 2001, have described the net joint moments and powers of the hindlimb in walking horses. These findings have been used to look at the effects of superficial digital flexor tendonitis on forelimb net joint moments and joint powers by Clayton et al., (2000) [60] and will continue to be the driving force behind studies applying the findings from this research to detect changes in energy profiles in other soft tissue injuries [59].

The use of force platform measurements alone can provide the ground reaction force patterns of normal horses, which show a number of characteristic peaks identified at the trot as a parabolic curve with an initial inflexion due to the rapid deceleration of the hoof as it strikes the plate (Figure 1) followed by the trace then rising smoothly to a peak at the midstance position after which it decreases to lift off [12, 52]. The ground reaction force patterns of lame horses show changes in amplitude and in the times that various peaks occur [64]. Collection of a standardized set of normal ground reaction force patterns provides an objective means of detecting injury [65].

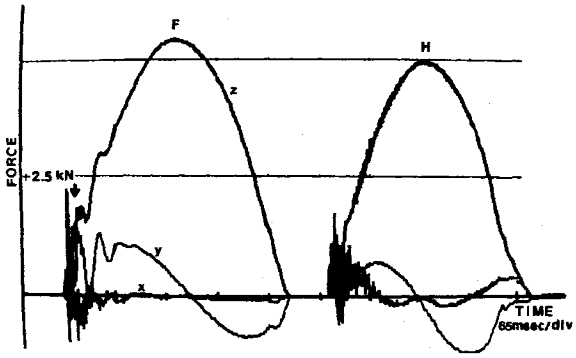


Figure 1 – Graphical output from a force plate. The graph shows normal output from a horse at a trot. Both a front (F) and hind (H) limb are represented with curves for vertical force (F_Z), and shear forces (F_y, F_x) plotted in a force – time curve [52].

The normal horse at a trot generally produces a parabolic curve with an initial inflection as the hoof strikes the platform (Figure 1) [53]. When a lame horse is trotted across the platform, the most obvious changes seen are a reduction in the vertical peak force and a 2 fold increase in the average craniocaudal force for front limbs lamenesses [52]. To continue to move forward with studies of ground reaction forces, some researchers have tested a force-measuring horseshoe. One of the first instrumented horseshoes was tested by Bjorck on draft horses [66]. However, this shoe was too heavy to be used at fast speeds. Barrey investigated vertical ground reaction forces using an easy boot (Les-Kar Inc.), which was fitted with a horseshoe containing 4 force transducers. The experiment looked at 20 sound horses and determined that the vertical hoof forces are not distributed uniformly over the whole hoof surface [67]. Kai et al. developed an instrument that could be sandwiched between the hoof and shoe. Using 2 metal plates, 4 load cells and 3 accelerometers, researchers were able to record vertical ground reaction forces and accelerations in 3 dimensions in horses at the walk, trot and canter. The force-time curves were similar to those obtained by force plates and the acceleration-time curves were similar to those recorded by accelerometers, suggesting that the shoe was reliably measuring actual forces and accelerations [68]. Although the technology behind force shoes is available, attaching them to the hoof in a manner that does not change the gait of the horse is still being developed. The overall advantage of using force-measuring horseshoes is that measurements of vertical ground reaction forces can be taken for consecutive strides and a variety of surface conditions.

1.5.2.2.3 Pressure Measurement Systems for Kinetic Gait Analysis

For over a century, scientists have been trying to perfect a system that would evaluate the structure and function of normal and pathological feet in order to objectively document the outcomes of treatments used for disorders of the musculoskeletal system [69, 70]. Scientists have used sacks filled with plaster of Paris as well as kinetographs to measure pressure distributions of the feet. The earliest kinetograph consisted of a deformable rubber pad that made contact with an inked paper placed underneath while the subject walked over the pad. The kinetograph measured maximal contact pressure [71]. These systems provided qualitative pressure evaluation but systems were still needed that could give quantitative data [69]. Using a load cell system that had piezoelectric sensors, scientists were able to quantify foot pressure data [69]. These new sensors were made of a thin, light, flexible material and the data was easily processed. Continuing development produced a system that consisted of rows and columns composed of interdigitated traces of silver-based, conductive ink screen-printed onto a Mylar substrate. As a force was applied to the mat, a proportional decrease in resistance took place. The pressure distribution was presented in an animated, 3-D color display [69]. These systems were the first technology to claim that they produce valid and reliable, plantar pressure measurements, as well as, being the basis for new systems to come [69].

Foot pressure measurement systems to date are designed in two basic types: Capacitive transducers have two capacitor plates separated by a compressible rubber dielectric material and force sensitive resistor (FSR) transducers are comprised of two thin layers of flexible plastic, with printed circuits on the inner surfaces, separated by a thin layer of double-sided adhesive with holes cut in for contact areas [28]. As pressure is applied to the capacitive transducer, the electrical resistance decreases which indicates an increase in pressure [28, 72]. The FSR systems are triggered by the application of pressure, which causes carbon on one surface to contact a metal pattern on the other surface, creating a resistive electrical current [28]. The accuracy and precision of these systems is dependent on the ability to reliably calibrate them as well as the rate the load was applied, amount of time the load stayed on the sensor, the size of the load applied and the age of use of the sensor [73]. These systems are valuable, because they provide a quick method of determining areas of high pressure. The two systems commercially available are mats and insole devices [28, 69, 71, 72, 74-76]. Pressure mats are used much the same as force platforms and provide a quick and easy method of obtaining pressure pictures as well providing information on load distribution over the surface, which force platforms cannot do [28]. Pressure mats can be used for testing of barefoot subjects, particularly for sizing of insoles in humans [71]. Also, the pressure mats are useful for testing of the diabetic patient as well as surgical patients who need to be tested barefoot [76, 77]. Pressure insoles were designed to give all the data of the pressure mats while testing multiple cycles with shoes on the subjects [28].

The pressure insoles make it easy to test pre- and post-orthotic wear with shoes on as well as evaluation of the diabetic and neuropathic foot while wearing shoes [75].

The use of foot pressure measurement systems has been critical in the advancement of the podiatric profession [75]. In-shoe pressure measurement systems have four primary areas of application. The first of these is detection of biomechanical abnormalities such as excessive supination and pronation, heel pain, and some foot deformities. These conditions make recognizable patterns that allow practitioners to make accurate diagnoses. The second area of application is preorthotic and postorthotic evaluations. Pressure measurement systems allow for the quantification of pressures exerted in specific areas. From this clinicians can evaluate the success of orthotic therapy. The third use of in-shoe devices is evaluating and predicting excessive pressure spots in the feet of diabetic patients and other diseased feet. The fourth use of in-shoe systems is presurgical and postsurgical evaluation of patients who have undergone osteotomies or bunionectomies. Testing allows for documentation of changes in surgical patients [70, 71, 75, 76, 78].

The F-Scan™ system (Tekscan, Boston, MA) is a computerized gait analysis system that uses FSR technology to measure plantar pressures [71]. The F-Scan™ system is composed of an ultra-thin, flexible sensor that consists of 960 sensing locations distributed uniformly over the plantar surface in the in-shoe sensors and over 2,000 sensors in the mats [71, 75, 77]. The EMED™ system

(Novel Gmbh, Munich, Germany) is designed as a capacitance transducer system. The EMED™ system has 99 capacitance sensors in each insole device [28]. The F-Scan™ and EMED™ systems have been used extensively for studying podiatric patients [75]. An advantage to using the capacitance sensors is that the output is less sensitive to temperature and humidity [79].

As with any system to be used for scientific quantification of test results, the accuracy and precision of gait analysis systems must be tested against known standards, such as the force platform, as well as the repeatability of the systems to measure accurately. Accuracy of gait analysis systems is a difficult parameter to test. Most of the equipment is designed to an accuracy of 10%, which needs to be considered when being used for research [74]. Most often an accuracy of 6 – 8% is required in research so that changes between normal and altered can be determined. An accuracy level of 10% could make it difficult to differentiate between the normal variability of subjects at different gaits and changes in gait due to a treatment effect [74]. Precision of measurements consists of two parts: (1) reliability of the testing device itself and (2) variability associated with gait patterns [80]. The reliability of the systems increases with the number of footfalls measured [80]. Reliability coefficients are measured as the proportion of variance of a subject due to subject-subject variability [74]. Coefficients with values between 0.4 and 0.75 indicated good reliability and coefficients greater than 0.75 indicated excellent reliability [74, 80]. Precision is a critical factor to look at in these systems because it represents the consistency of a measurement [81]. This is particularly important in measuring pressure changes because the ability of the system to obtain consistent, repeatable measurements is critical [81]. The accuracy of the system is based on its ability to measure a true value, when compared to a "gold standard", in this case the force platform is the accepted true value [81].

The precision of measurements can be easily affected by changes in gait speed. Changes in speed at which the data is collected can cause significant changes in pressure and force values. An example of this is seen in humans in testing at greater speeds is associated with increased peak forces in the heel and toe regions [74, 80]. This suggests that the speed range for data collection should be carefully assessed.

Pressure measurement systems that are made using the FSR technology tend to have increasing error when heavy, static loads are applied [81]. Additionally, these systems only show a moderate level of repeatability between dynamic trials [81]. On the other hand, the capacitance technology shows minimal error in pressure readings at various levels of static loading. In addition, the capacitance systems show a high level of repeatability between trials and these systems show less creep during application of continuous pressure [81]. Tests of the FSR gait analysis systems have shown that the use of this type of technology in research should be questionable. The tests indicate that FSR systems might not accurately calculate plantar pressures in humans [81]. Other researchers compared the two pressure measurement systems as well. Luo et al. showed that the FSR systems had errors as high as 20% with most of the errors occurring at low-pressure levels [82]. Woodburn et al. noted that the FSR technology showed limited durability [83]. Xia et al. found that both the FSR technology and capacitance technology showed a significant difference in measurements between 2 days and concluded further testing was needed to look into the repeatability of both systems for tests longer than 2 days [84]. Hsiao et al. found that the accuracy and precision varied across levels of applied pressure, calibration procedure, duration of pressure application and insole age of use [73]. The capacitance system showed greater accuracy and precision when the insole was new and measurements were taken after a manufacture-specified calibration procedure, in a range greater than 50 kilopascals (kPa) but less than 500 kPa and within a few seconds after pressure was applied [73]. For the FSR system, when the applied pressure was comparable to the calibration pressure, the measurement error was low. However, when the applied pressure was not in the calibrated range the system error was between –26.3% and 33.9% [73]. The system may be affected by nonorthopedic variables such as speed the subject is tested. In the case of an animal, the control on movement the handler has in addition to the accuracy of calibration and the ability of the system to function properly as the equipment begins to wear from testing.

Carter, et al. used the F-Scan™ human, in-shoe system in horses to test the precision and durability of this system for determining the ground reaction forces and temporal relationship of hoof strikes in the forelimbs of horses. Lameness was diagnosed by comparing the measurements of maximum force, stance time and contact area between left and right forelimbs. The lame forelimb was determined by a lower maximum force, shorter stance time or reduced peak contact area in comparison to the opposite forelimb. It is believed that at least three trials should be completed for greater precision of stance time and maximum force measurements [85]. Future studies using this technology need to test the accuracy of the system against a force platform, the known gold standard for objectively measuring lameness.

Investigators at Colorado State University used the F-Mat™ system in horses to test the precision of the system while objectively measuring lameness in the horse. Lameness was diagnosed by comparing measurements of force, pressure and contact area before and after surgically induced lameness [1].

Investigators used two different experiments to test the ability of the F-Mat™ system to measure subtle changes in gait. In the first project (Microfracture), investigators used twelve clinically normal horses, 2 to 5 years of age.

For surgery, each horse was put under general anesthesia and underwent arthroscopy to have a defect created in the medial femoral condyle of both hind limbs. A 1 cm^2 defect was created on the axial weight-bearing portion of the medial femoral condyle at the level of the medial tibial eminence. In all of the horses subchondral bone plate microfracture was performed within the defects. In one joint the defect was created to a depth leaving calcified cartilage intact, followed by microfracture treatment, while in the other joint the defect was created to a depth leaving the subchondral bone plate intact with microfracture treatment [1, 86].

Objective evaluations were done using the F-Mat™ system to measure *in vivo* vertical ground reaction forces. The horses were tested preoperatively, 4 months post-surgery and every 2 months thereafter until the conclusion of the project at 12 months after initial surgery [1].

In vivo ground reaction forces were setup to be measured using the F-Mat™ system. Infrared laser timed devices were used to monitor the speed at which the horses were trotting. (Figure 2) [1].

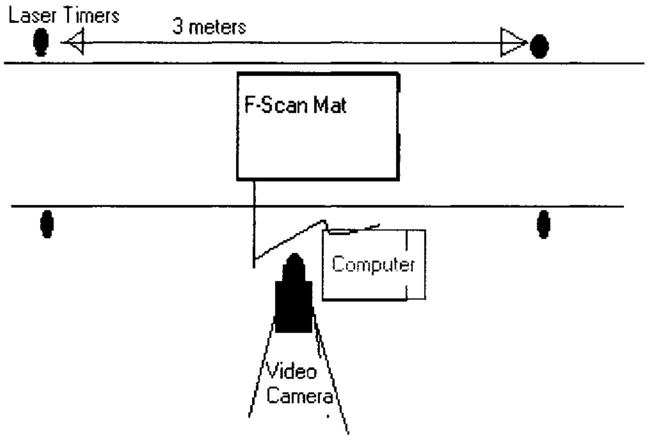


Figure 2. Chute setup for data collection with the F-Mat™. The chute is 15.2m long and 0.8m wide. The mat lies on the ground in the center of the walkway and the horses trot back and forth across it. Speed is monitored by infrared timers set at the edges of the chute and a video camera records the horse's movements [1].

During testing, the horses were trotted through the chute at a target rate of 2.6- to 3.3-m/s. The speed of travel was monitored by laser timers, and reflected by times between 0.95- and 1.15 seconds. From those hoof strikes, measurements of pressure, contact area and force were collected for later analysis [1].

A mixed model analysis of variance using SAS (Statistical Analysis System, Cary, NC, USA) was used to evaluate the dependent variables, which included maximum pressure, maximum force and maximum contact area. A P-value $\leq$ 0.05 was considered significant. Normalization to one limb was done to test for drift over time within the system as a measure of precision. Coefficients of variation were done to report the precision of the system for the amount of data collected [1].

Throughout the study the horses were tested on the F-Mat™ system on the scheduled dates. Maximum force, and maximum pressure data showed a significant decline in values over the one-year testing period (Figure 3 and 4) [1].

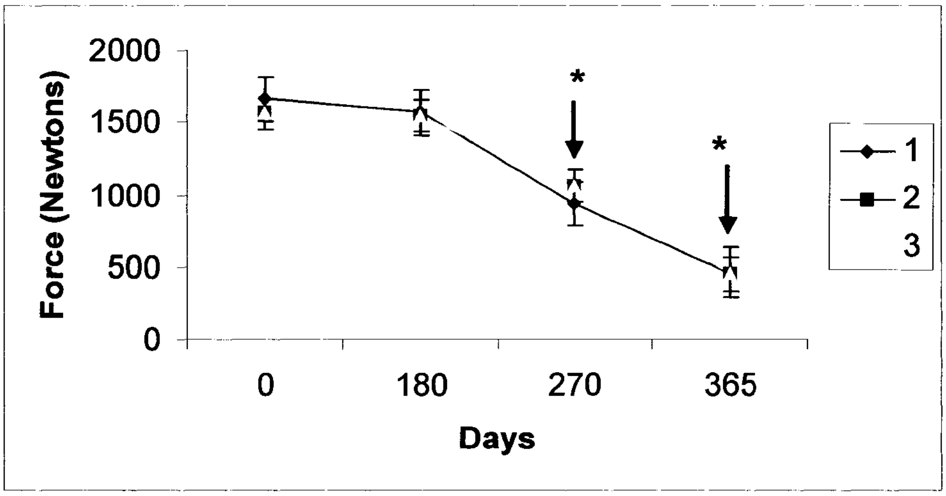


Figure 3 – The force Measured from hoof strikes recorded on days 0, 180, 270 and 365. The effects of treatment were being tested over time. Treatment groups are labeled; (1) Hind limb containing a defect without calcified cartilage present, (2) Hind limb containing a defect with calcified

cartilage present, and (3) Average of the front limbs. Asterisks (*) denote a statistical difference (P – value < 0.05) in the data compared to calculated forces on prior testing days [1].

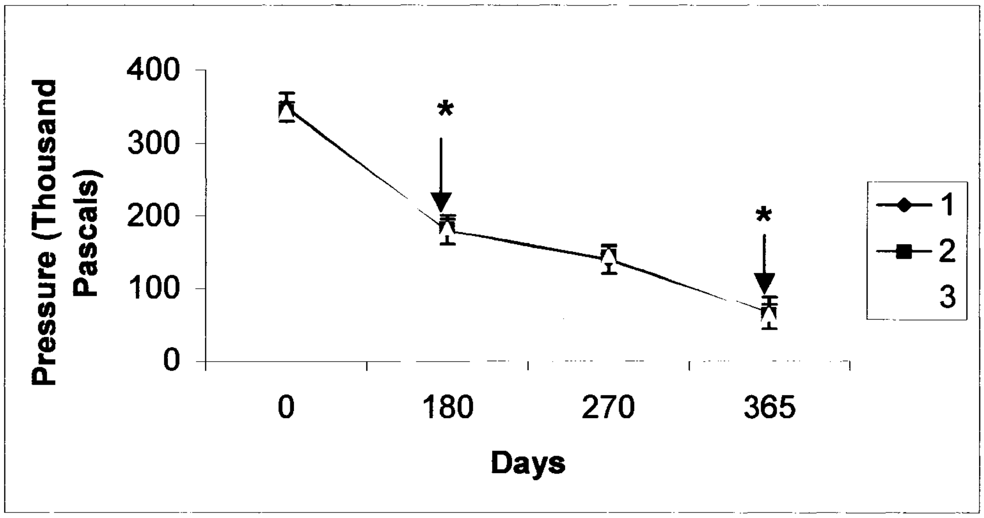


Figure 4 – Maximum pressure calculated in Kilopascals ($N/m^2 * 1X10^3$). The treatment effects are labeled; (1) Hind limb containing a defect without calcified cartilage present, (2) Hind limb containing a defect with calcified cartilage present, and (3) Average of the front limbs. Asterisks (*) denote a statistical difference (P – value < 0.05) in the data points compared to the testing date prior to those measurements [1].

Because no apparent change in body weight occurred in these horses, the cause of the steady decline in the data suggested there was drift over time. To test this, data was normalized to one front limb at that given time point. No difference was then detected over time. Using this analysis method it appeared limbs that underwent surgery had significantly higher-pressure readings than the forelimbs at 180 days (Figure 5). There was a significant change in force measurements after normalization in horses with no calcified cartilage compared to the front limbs (Figure 6). Also, there was a significant change in force calculations from 0 to 180 days in horses with no calcified cartilage (Figure 6). Contact area measurements showed no significant differences between treatment groups. Although there were significant changes in contact area noted over time in each of the groups (Figure 7). All treatment groups showed an increase in contact area from 0 to 180 days followed by a decrease from 180 to 270 days and another increase from 270 to 365 days [1].

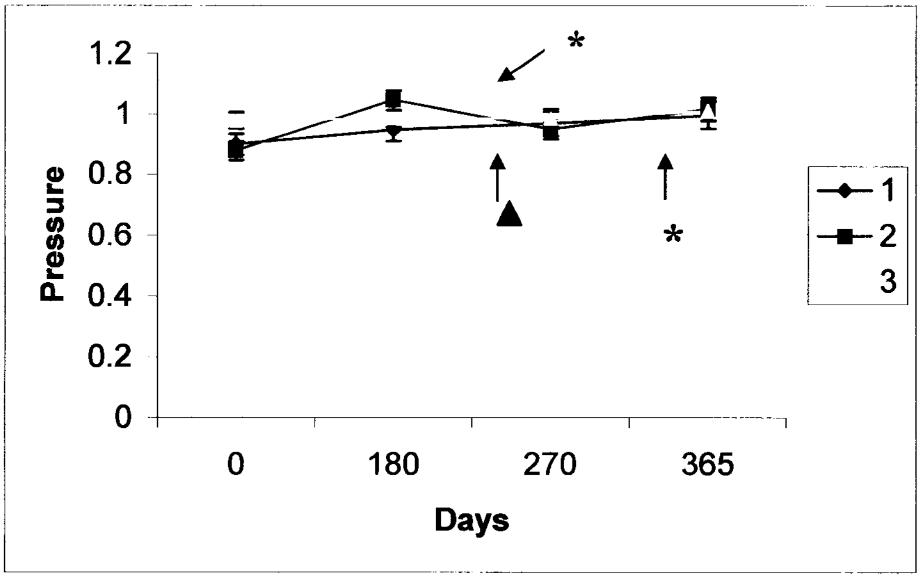


Figure 5 – Maximum pressure normalized to a left front limb. The graph represents the interaction of treatments; (1) Hind limb containing a defect without calcified cartilage present, (2) Hind limb containing a defect with calcified cartilage present and (3) Average of the front limbs over time. Asterisks (*) denote a statistical difference (P – value < 0.05) in the data points compared to the prior testing date. A triangle denotes a statistical difference between treatment groups 1 and 2 on day 180 [1].

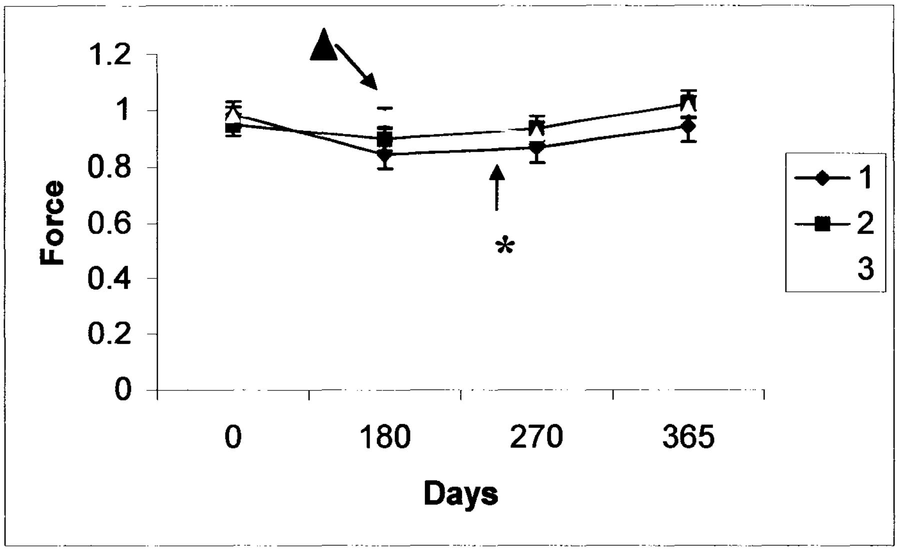


Figure 6 – the graph represents maximum force normalized to the left front limb. Treatments are labeled; (1) Hind limb containing a defect without calcified cartilage present, (2) Hind limb containing a defect with calcified cartilage present, and (3) Average of the front limbs. Triangles denote a statistical difference (P – value < 0.05) between treatment groups 1 and 3 at day 180. An asterisk (*) denotes a statistical difference in treatment group 1 between days 0 and 180 [1].

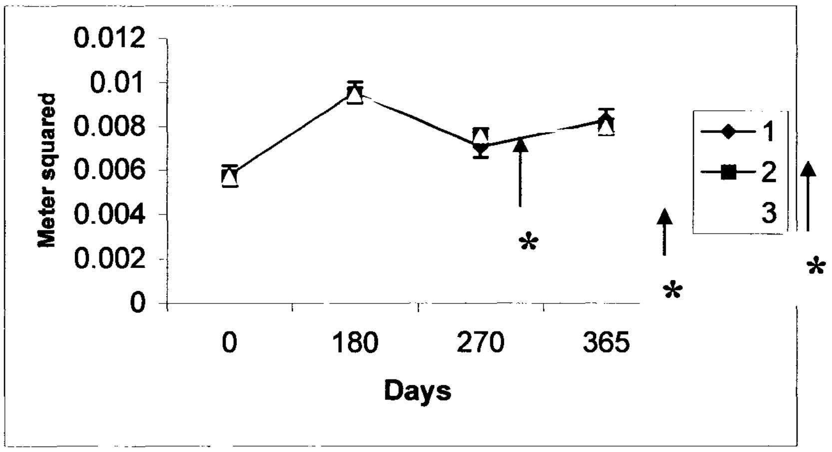


Figure 7 – The maximum contact area measured in meters squared on designated testing days. Treatments are labeled; (1) Hind limb containing a defect without calcified cartilage present, (2) Hind limb containing a defect with calcified cartilage present, and (3) Average of the front limbs. Asterisks (*) denote statistical difference (P – value < 0.05) in contact area measurements for all treatment groups from the prior testing date to the one marked. At day 365, contact area only increased significantly in treatment group 1 [1].

Coefficients of variation were calculated for maximum pressure, force, contact area as well as area under the curve for force and pressure. Values ranged from 12- to 32% (Figure 8) [1].

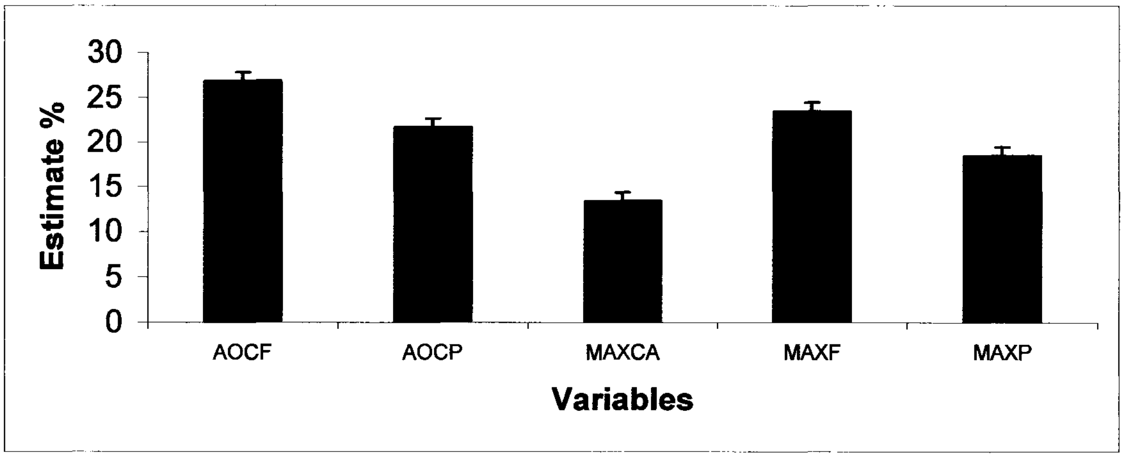


Figure 8 – Estimates of coefficients of variation for the variable analyzed. Area under the curve (AOC) is measured for force (F) and pressure (P), while maximums were measured in contact area (CA), force and pressure [1].

In the second study (Gene Therapy) conducted by investigators at Colorado State University, sixteen clinically normal horses, 2 to 5 years of age were studied [87].

The horses were divided into two groups: treated and placebo. All horses had an osteochondral fragment created in one randomly selected intercarpal joint, while the opposite joint served as a control. Eight horses received an Intra-articular treatment with an adenoviral vector carrying equine IL-1Ra 14 days after surgery in the joint containing the fragment. The opposite joint was treated with a dose of balanced salt solution equal in amount to the limbs treated with IL-1Ra [87].

Horses were trotted through the 15.2-m long chute containing the F-Mat™ for acquisition of vertical ground reaction force data. The horses were trotted at a rate of 2.6 to 3.3 m/s through the infrared laser timers set 3 m apart with the F-Mat™ equidistant from the timers [1].

Data collection occurred pre-operatively, 14 and 70 days post-surgery. Day 14 data acquisitions occurred before the horses were treated with the equine IL-1Ra therapy. Pressure, contact area, contact time, force, pressure*time and force*time were analyzed from the recorded data [1].

A mixed model analysis of variance was performed using Proc Mixed. Day of testing, presence or absence of a chip, and treatment with Ad-EqIL-1Ra or placebo were defined as the independent variables in the model. Correlations between maximum force and subjective lameness scores were also conducted [1].

The highest degree of lameness was a grade 3 in one horse and all other horses were evaluated at a grade 1 in at least 1 limb. Analyzing lameness examinations performed 70 days after surgery demonstrated that limbs with a joint containing a fragment and receiving placebo treatment had higher lameness scores compared to limbs with a non-fragment joint (Figure 9). No statistical difference was noted between limbs in the horses treated with Ad-EqIL-1Ra (fragmented or non-fragmented), however, limbs that contained treated, fragmented joints were less lame compared to limbs containing fragmented joints in placebo treated horses (Figure 9) [87].

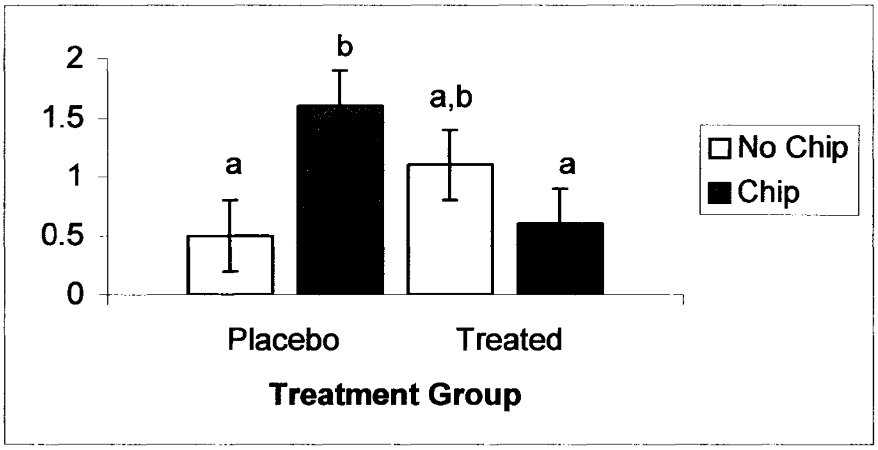


Figure 9 – Day 70 lameness scores plotted by treatment group. Different letters indicate a statistical difference (P – value <0.05) between bars [87].

The horses were tested on the F-Mat™ system three times during the duration of this project. Analysis of data showed no significant differences between treatment groups until day 70 (Figure 10). At day 70, limbs of placebo treated horses with fragmented joints placed significantly more force on the injured limb than did horses that had fragmented joints and were treated with Ad-Eq-IL-1Ra (Figure 10). No statistical difference was seen between horses treated with Ad-Eq-IL-1Ra with chips and horses without chips treated with Ad-Eq-IL-1Ra (Figure 10). There were significant differences in force measurements in the placebo treated groups from 0 to 14 and then 14 to 70 days (Figure 10) [1].

Impulse measurements for force showed the same trends as maximum force calculations indicating a relation to the stance time of the hoof [1].

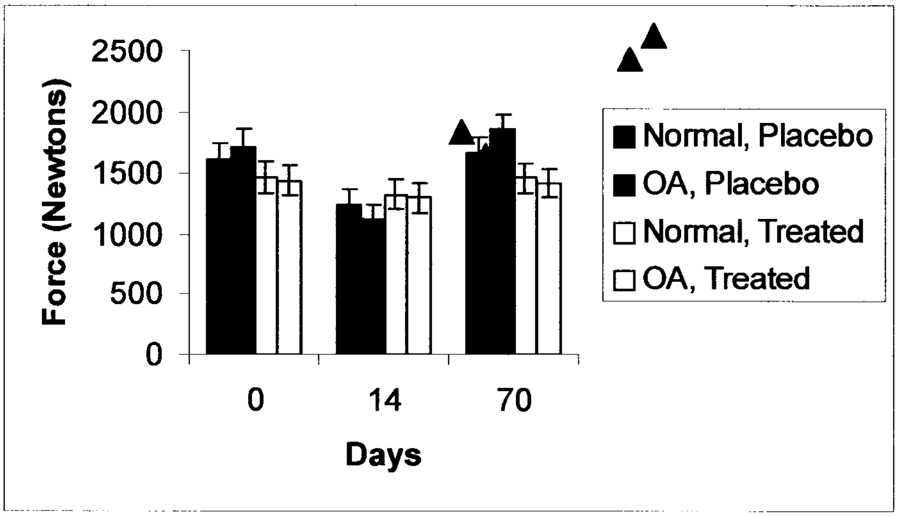


Figure 10 – Force calculations plotted by treatment and surgery group on each day. Triangles indicate a statistical difference (P-value <0.05) between the same groups over time. At day 14, placebo treated groups had significantly lower force measurements than the same groups at day zero. The same groups then had significantly higher measurements at day 70 [1].

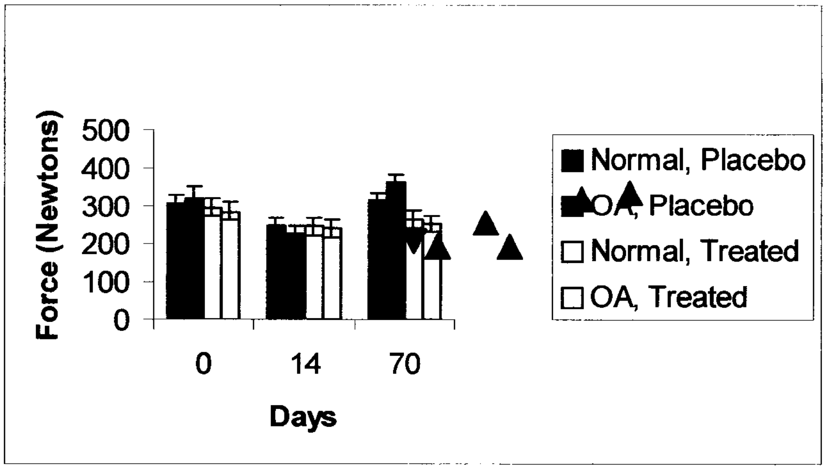


Figure 11 – Area under the curve for force. Force/time plotted by time looking at treatment and fragmented or not fragmented. A triangle indicates a statistical difference (P-value <0.05) between the same groups compared over time. At day 14, all groups showed significantly less force/time than at day zero and at day 70, placebo treated groups had significantly higher force/time readings than the same groups had at day 14 [1].

Pressure measurements indicated a significant decrease in overall measurements from day 0 to day 70, particularly in the treated groups (Figure 12).

In addition, horses with treatment of Ad-Eq-IL-1Ra had significantly higher-pressure readings than placebo horses (Figure 12) [1].

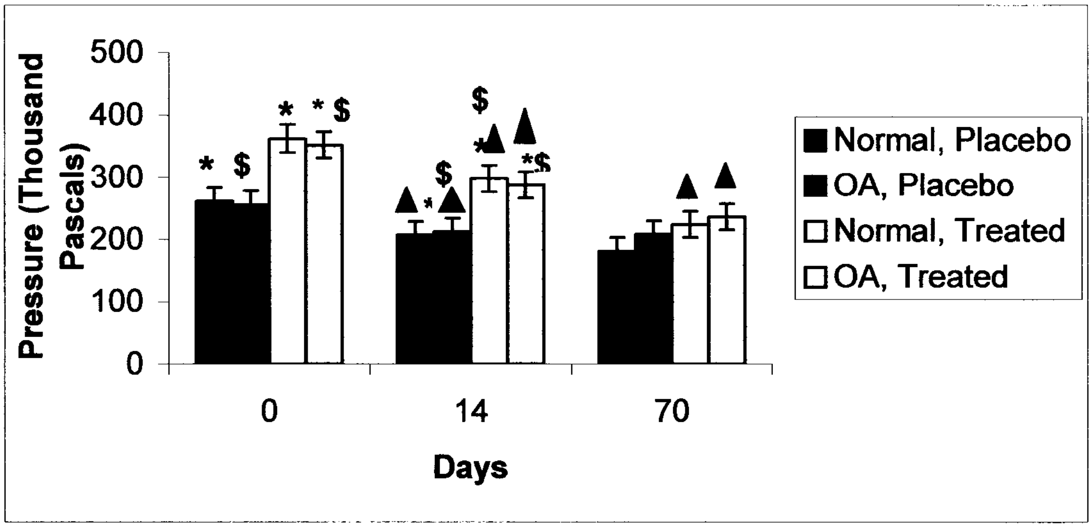


Figure 12 – Maximum pressure plotted by days looking at the effects of treatment and chip or no chip. Asterisks (*) indicate a statistical difference (P – value <0.05) between different groups at the given time point. At day zero and day 14, groups treated had significantly higher-pressure values than a non-fragmented, placebo treated joint. The dollar sign ($) indicates a statistically significant difference between fragmented, placebo treated joints and joints receiving treatment at day zero and 14. A triangle denotes a statistical difference between the same groups compared over time [1].

Significantly larger contact areas were measured in the placebo groups compared to treated groups on day 0 and day 70 (Figure 13). This indicates a random chance that a greater number of horses with smaller hooves were placed in the treated groups. This trend is further emphasized in the readings of contact time. The groups treated with Ad-Eq-IL-1Ra had shorter contact times indicating that horses with small hooves spend less time in the stance phase and thus hit harder causing more pressure to be sensed in the mat (Figure 14) [1].

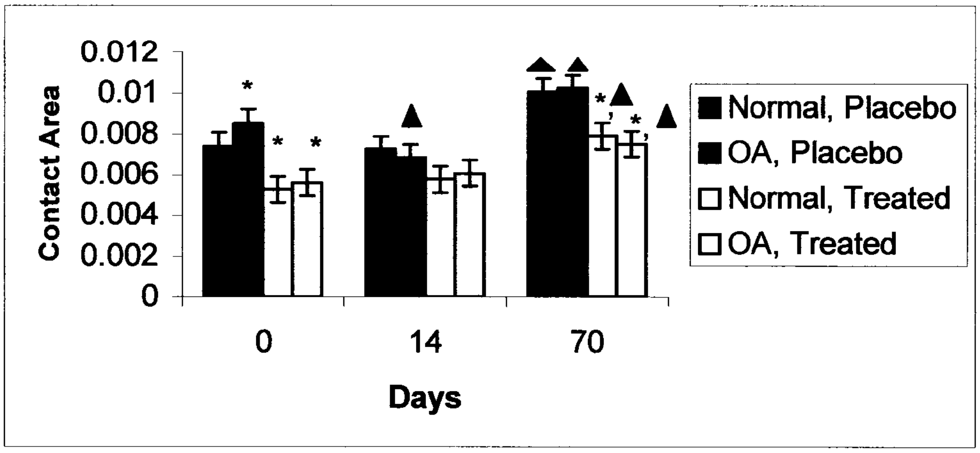


Figure 13 – The graph represents maximum contact area in m^2 plotted by day for categories of treatment and surgery type. Asterisks (*) indicate a statistical difference (P-value <0.05) between different groups at the given time point. On day zero, groups with treatment had significantly less contact area than the placebo groups. A triangle denotes a statistical difference between the same groups compared over time [1].

A calculated correlation coefficient between subjective lameness exams and maximum force measurements at day 70 showed an R-Square value of 0.0239 indicating very little association between the two variables [1].

Investigators at Colorado State University concluded that the F-Mat™ was not capable of objectively assessing lameness in the format tested. More experiments needed to be conducted to test the accuracy of the mat system against a force platform as well as looking at the effects of different calibration levels on overall force and pressure measurements.

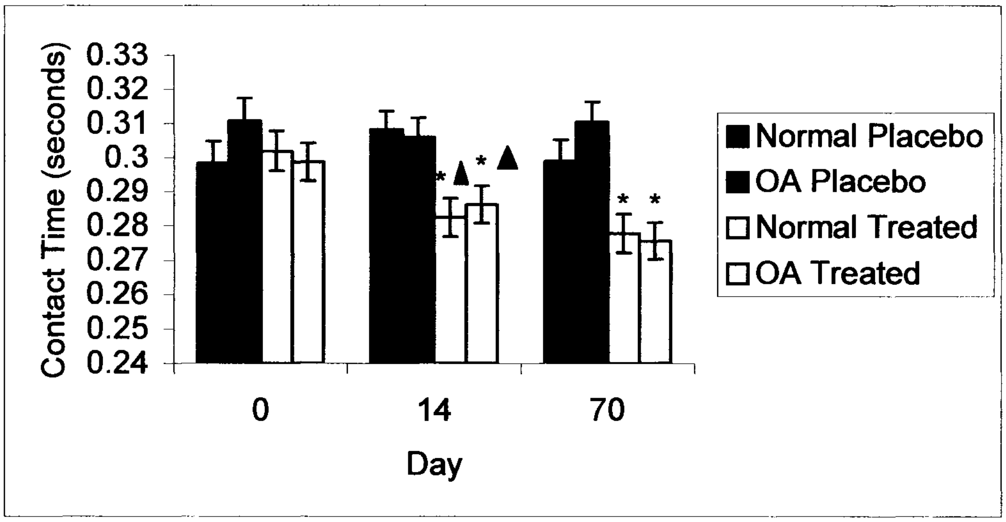


Figure 14 – Contact time is the time the hoof spends on the mat during the stance phase. Asterisks (*) indicate a statistical difference (P-value <0.05) between groups at the given time point. A triangle denotes a statistical difference between the same groups compared over time [1].

1.5.2.2.4 Fuji Film for pressure measurement

Fuji pressure sensitive film has been used widely for the study of contact mechanics in artificial joints [88-91]. The film is supplied in five grades, designated as ultra-superlow, superlow, low, medium and high which together allow interface pressures between 0.2 and 130 mega-pascals (MPa) [90-92]. The first three grades of film (super-low, low and medium) consist of an A-film and a C-film both of which have an active coating of polymer substrate. On the A-film, the active coating consists of microscopic bubbles. These bubbles burst on the application of pressure, releasing an amount of colorless liquid relative to the number of bubbles burst. The active layer on the C-film reacts with the liquid from the A-film, producing a pink stain [92]. The high grade film is a single sheet, consisting of a polymer substrate with an active layer consisting of both the bubbles and the color-developing material [92]. Fuji film has been used to measure contact pressures and contact area in articulating and artificial joints [91, 93]. Clark et al. noted that because pressure sensitive film records all pressures applied during measurement, sliding of joint surfaces could cause overestimation of contact areas and pressures [93]. Fuji-film provides an inexpensive method of providing contact areas and contact pressures when the accuracy and precision of a system are not extremely important. Because the films only develop from the minimum to the maximum of their specific ranges it can be difficult to determine the correct film to use and then if excess pressure is applied the film may overestimate the contact area and pressures. When testing hoof pressure, overestimations can occur if there is an uneven contact surface between the film and the hoof. In addition, multiple landings on the film can cause over development, which would lead to overestimation of contact pressures.

1.5.3 Conclusion

Technology to objectively assess lameness in horses is available. The current challenge is to find technology that is capable of providing accurate, precise, reproducible data. The system needs to be sensitive enough to identify subtle gait changes caused by lameness even at high speeds. Also, the system should be user-friendly, providing rapid results that a clinician could evaluate immediately after testing [18]. Continued testing of new systems based off of old and new technology will eventually provide the desired system for equine gait analysis that can be used both in research and in the clinical setting.

CHAPTER 2 Testing the Accuracy of the F-Mat™ system and the effect of changing speed on vertical force measurements.

2.1 Introduction

Pressure measurement systems may provide the technology to quantitatively assess lameness. The F-Mat™ (Tekscan, Boston, MA) is a thin film sensor mat designed to measure pressure as a human subject steps on the mat's surface. Pressure mats are placed in the center of a walkway and used much like a force plate. The subject walks down the walkway, stepping on the mat. The data quickly and easily provide the clinician with information on force, contact area, plantar pressures, impulse and pressure*time integrals [94].

The F-Mat™ is a device containing over 2,000 sensing cells that measure force and contact area [77]. Contact area is measured based on the number of sensors activated by the pressure placed on the mat [77]. Force is measured by the amount of electrical resistance produced [94]. The system records data as vertical force and contact area measurements and then calculates pressure. As recordings are taken, the system measures vertical force from time of first contact until the pressure is removed from the mat [77]. The system can then be used to analyze frames of the recorded pressure contacts and based on the selected hoof prints, contact area and vertical force are recorded, and pressure is calculated [77]. This system is designed to test *in vivo* vertical ground reaction force measurements. By editing the recorded movie, an observer can select a given number of frames of pressure recordings to be evaluated. From this data, the recorded measurements can be grouped into one composite phase and from that the system gives maximum force, contact area and calculated pressure values. The composite phase allows the investigator to look at the maximum pressure value that each sensor reached during that phase [77]. In addition, the system is capable of calculating the area under the curve for the composite phase in measurement units of impulse and pressure*time [77].

2.2 Question 1: Does speed influence the variability of the F-Mat system?

Original testing of the F-Mat™ system by investigators at Colorado State University raised questions as to why the coefficients of variation for the project were so high (12-32%). One thought was that the speed the horses were trotting across the mat was too variable. Therefore, investigators evaluated the speed at which the horses were traveling by breaking the 12 horses from the Microfracture project into groups with time ranges of 0.95 -1.04 s and 1.05 -1.15 s. Then the coefficients of variation were recalculated with the following results (Figure 15). Coefficients of variation were calculated for each horse at each trotting speed. Results showed that ten horses had higher calculated coefficients of variation when traveling 3 meters in the time range of 0.95 – 1.05 seconds (3.15 m/s to 2.85 m/s). When the rate of travel was decreased to a range of 2.85 m/s to 2.6 m/s, in the time range of 1.05 – 1.15 seconds, the calculated coefficients of variation for the majority were less than at the higher rate of travel.

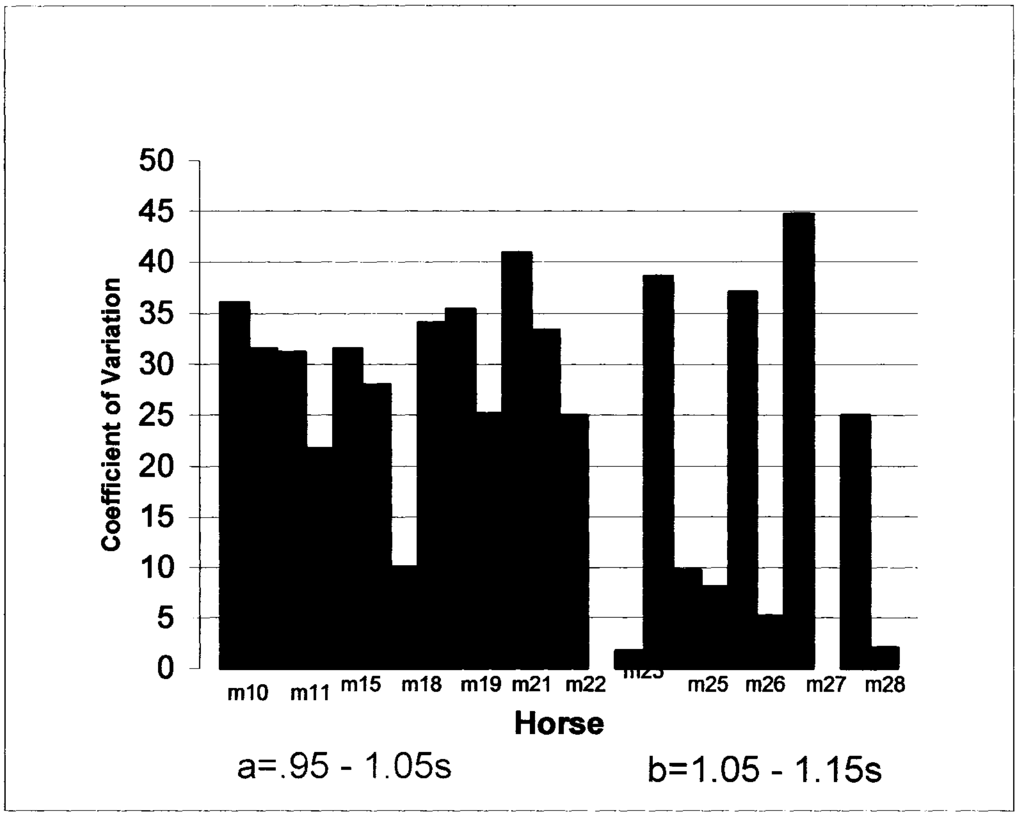


Figure 15 - Coefficients of variation for each individual horse are represented at one testing time. Maximum force data were collected at two speed ranges and then investigators calculated coefficients of variation to see if trotting speed influenced the variability of the system.

Conclusions from this showed that for this group of horses, the variation in measurements was less when horses were trotted slower. However, this was not conclusive because several of the horses had results opposite of the other horses. These horses had increased variability when they traveled slower. This led investigators to believe that other environmental factors such as temperature at testing, and handler effect may have been affecting the variability of the maximum force measurements as well.

2.3 Question 2: Will changes in calibration load affect the ability of the F-Mat system to objectively assess lameness in the horse?

After examining data from the horses in the Gene Therapy project, investigators suspected that a calibration error might be causing an error in analysis that was showing the limb that was most lame to have the most force on it. Investigators were able to change the calibration matrix within the software for the mat system and use a weight value closer to the actual weight of the horses. The results are shown in Figure 16.

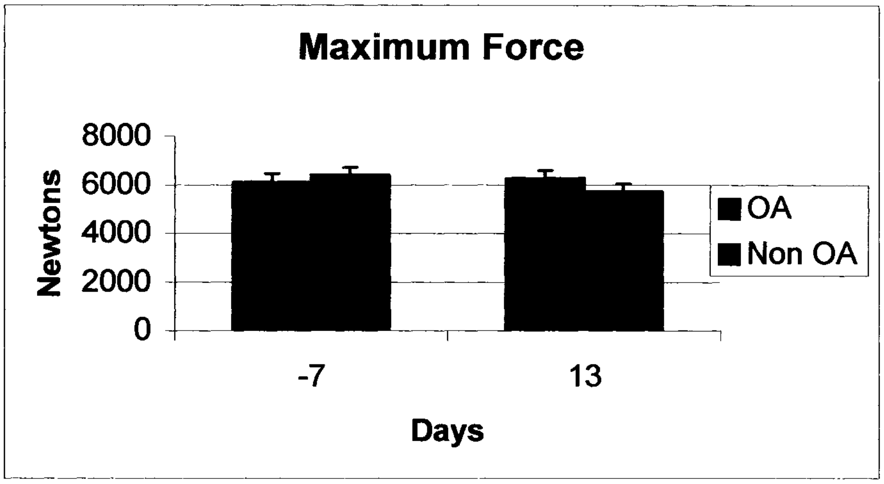


Figure 16 – Measurements of force values are represented from baseline data and data taken after surgery. The diseased limb and control limb were normal at –7 days and the disease limb contained an osteochondral fragment at day 13.

Investigators were able to see the correct pattern in the data from baseline measurements. The baseline measurements occurred at –7 days and the maximum force measurements from the limbs were close enough in value that no significant differences were noted between right and left forelimbs. By day 13, the osteochondral fragment had been created and the limb with the fragment appeared more lame when evaluated subjectively. However, this was not noted by analyzing maximum force data in which the diseased limb had higher maximum force values when compare to the control limb. These results were opposite of the subjective lameness evaluations in which the diseased limb scored higher on the AAEP grading scale (Figure 9). Results from this test indicated that the diseased limb had more peak force applied through it than the control limb.

2.4 Question 3: Will the F-Mat™ system be as accurate as a force platform?

Materials and Methods

At this point in time, investigators realized that with the saturation level of the F-Mat™ designed for humans it was possible that the system was not able to accurately measure vertical ground reaction forces because it was saturated long before the maximum vertical force measurement had occurred. At this point, investigators wanted to test the accuracy of the F-Mat™ system against a force plate. This test would allow investigators to examine data collected simultaneously from both systems and determine if the F-Mat™ truly could be used as a tool for objectively measuring lameness in the horse.

Animals - Eight horses, 2 to 5 years of age were studied. Horses were in good health and free of lameness before and after carpal flexion. All horses received an intra-articular injection of endotoxin in one carpal joint to create synovitis. In addition the horses were treated with phenylbutazone, lidocaine or saline for pain management.

Calibration Procedures - Prior to testing, the force platform and F-Mat™ systems were calibrated and checked for proper function.

Force Platform Calibrations - The force platform (Model 6090-15, Bertec, Inc. Columbus, OH, USA) was set to a recording speed of 1200 Hz, and static weights were loaded onto the plate over a 2 minute interval to test the accuracy of the force platform. Twenty, 23 kg weights were stacked onto the plate until 460 kg was on the plate and settled, then the weights were removed one at a time. The data collected were analyzed for maximum vertical force measurements and verified to the actual vertical force applied as calculated by the equation F=mg (F =force (N), m = mass (kg), g =gravitational acceleration (m/s^2).

Calibration of Force Platform and F-Mat™ - The F-mat™ and force platform were calibrated with a static load of 363 kg prior to testing.

Data Collection - All horses were trotted through a chute 15.2 m long and 1 m wide containing the F-Mat™ lying over the force platform with a 3 m long thin rubber mat placed over the mat for protection. The force platform was set to a recording speed of 1200 Hz and the F-Mat™ recorded at a speed of 125 Hz. The horses were trotted at a rate of 2.6 to 3.3 m/s through the infrared laser timers. Data collection continued until 5 whole hoof strikes from each limb had been recorded on the force platform and F-Mat™. Data were collected before the first endotoxin injection, 6, 12, 24, 36, 48, 72 and 96 hours after injection. However, only baseline data were used for assessment of the accuracy of the F-Mat™ system.

Data Processing

Data from the F-Mat™ and force platform were analyzed for maximum force values from the stance phase. No filtering was performed on measurements from the force platform or F-Mat™.

Statistical Analysis

A paired t-test was used to compare the maximum force values from the F-Mat™ compared to the force platform to test the accuracy of the F-Mat™ system. Coefficients of variation were calculated to report the precision of the system for the amount of data collected. Differences were considered significant whenever the P value was < 0.05. A correlation with the dependent variable as maximum vertical force measurements from the F-Mat™ and independent variable as maximum vertical force measurements from the force platform was calculated using SAS (Statistical Analysis System, Cary, NC, USA) to check for a linear relationship between the measurement systems and test the accuracy of the F-Mat™. The correlation coefficient was noted between the force platform and the F-Mat™. A Bland-Altman test for measuring agreement was also used to test the precision and accuracy of the F-Mat™ compared to a force platform [95]. The limits of agreement were set at ± the standard deviation of the differences. If the mean and all calculated differences were within the limits of agreement, then the F-Mat™ was as accurate as a force platform [95]. The precision of the F-Mat™ was tested by determining if the limits of agreement were within the 95% confidence intervals calculated for the limits of agreement [95].

Results

The accuracy of the force platform was checked using static weights. The weights were placed on the force platform and measurements were taken. With 460 kg of weight on the platform, the readings did not vary by more than 4.6 kg (1.0%) (Figure 17).

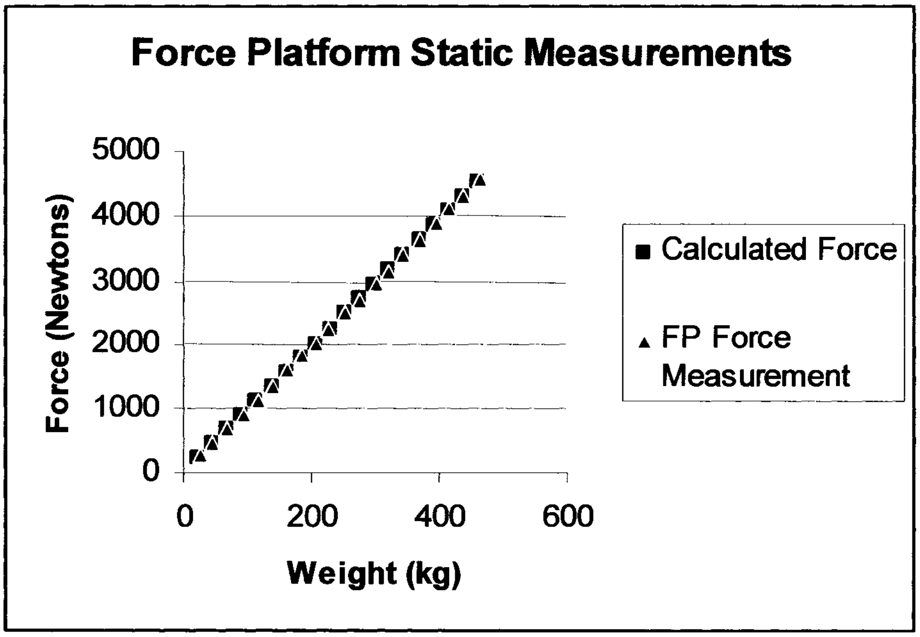


Figure 17. The accuracy of the force platform was checked by placing 20, 23 kg weights on the plate. Those measurements were then plotted against the calculated force values for each mass.

Significant differences were noted between maximum vertical force measurements from the F-Mat™ system and force platform (Figure 18).

A correlation was calculated to test for the linear relationship between force measurements from the F-Mat™ and force platform for individual measurements (Figure 19). The calculated coefficient of correlation between measurements from the two systems was 0.127.

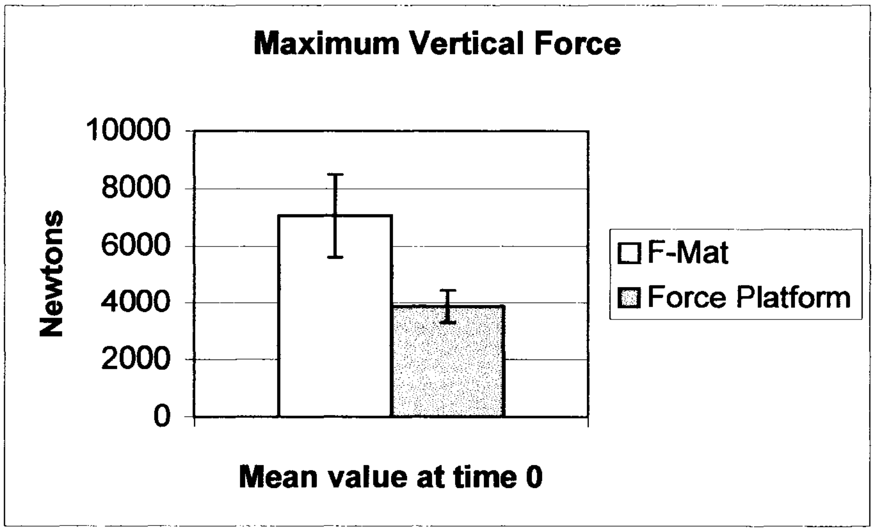


Figure 18. The mean values for the vertical ground reaction force measurements from the F-Mat™ and force platform. There is a significant difference calculated between the means with a p-value of $p<0.05$. This graph represents data from a collection before endotoxin was injected into the joint. The y-axis is representative of a force measurement in Newtons.

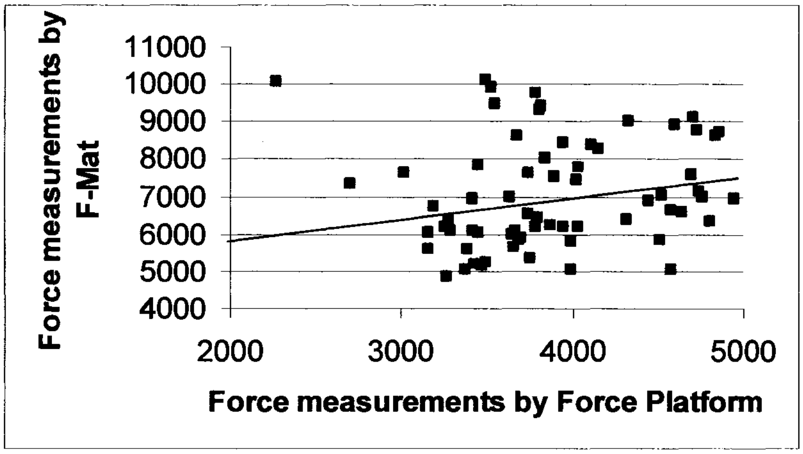


Figure 19. A scatter plot of the F-Mat™ force versus the Force Platform force (Newtons). The regression line, F-Mat™ force = 5821.53*0.3183 (Force platform force). The $r^2 = 0.016$ and the correlation coefficient = 0.127.

The Bland-Altman test for measuring agreement showed a wide range for the differences with limits of agreement set at –227 N and –6,135 N. The calculated differences ranged from –478 N to –7,798 N (Figure 20). The wide range of differences indicated the F-Mat™ system was not as accurate as the force platform. In addition, the precision of the limits of agreement was calculated. The 95% confidence intervals for the limits of agreement were wide with ranges for the upper limits from –5,616 N to 291 N and the lower limits from –6,653 N to –745 N, reflecting great variation in the differences indicating a lack of precision in the measurements. Coefficients of variation were calculated for the F-Mat™ system at 10% and the force platform at 7% to monitor precision of the systems as well.

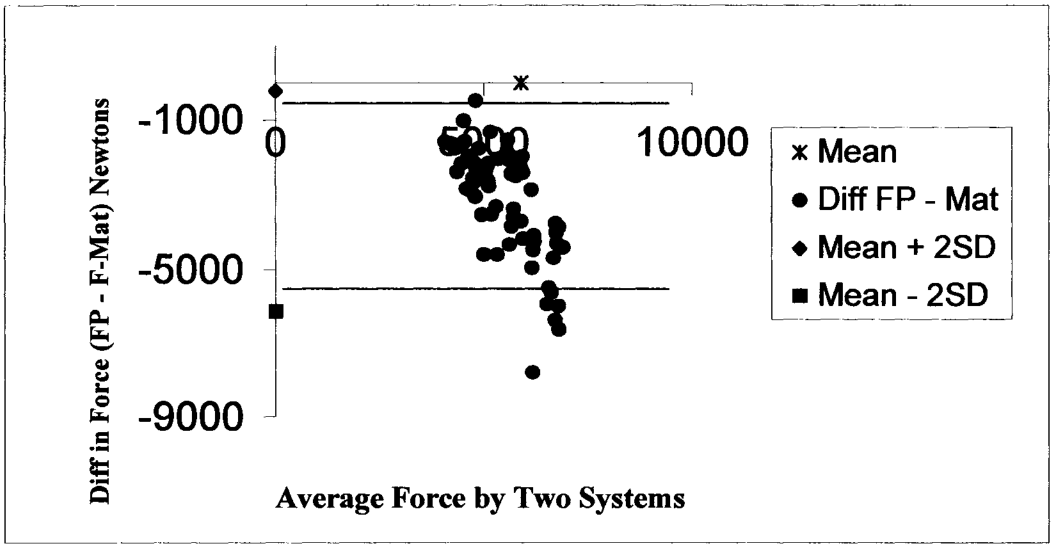


Figure 20. Differences in vertical force measurements plotted against mean vertical force measurement data from the force platform and F-Mat™. The limits of agreement were marked by lines at ± 2*sd of the differences. The differences were plotted in the negative y-axis, which indicated values from the F-Mat™ were greater than measurements from the force platform. Large differences between measurement devices indicate bad agreement.

Conclusions

All of these projects encouraged investigators to continue testing the pressure measurement system because the system still provided a relatively inexpensive means of objectively measuring lameness.

Investigators tested the accuracy of the mat system by comparing vertical force measurements from the mat to a force platform. Comparison of the mean values from these measurements showed a significant difference between the force platform and mat measurements. A correlation showed little relationship between measurements from the two devices. In addition, calculations from the Bland-Altman test indicated bad agreement between the differences further concluding the mat was not as accurate or precise as a force platform. Finally, a calculated coefficient of variation of 10% for this project and even higher variations for other tests indicated to investigators that in the current testing environment, the measurements of vertical force from the mat were not accurate or precise enough to persuade the investigators to use the mat system as a tool for objectively assessing lameness in the horse.

The accuracy tests comparing the F-Mat™ to a force platform indicated that the F-Mat™ system designed for humans was saturating as seen by maximum vertical force measurements from the force platform that were several thousand Newtons lower in value than measurements from the F-Mat™ system. Due to the saturation, the F-Mat™ system had not been capable of recording vertical force measurements accurately and therefore the calculated vertical force maximums had been extrapolated based on maximum calibration loads and the pressures those loads applied. Due to this, the F-Mat™ was not accurate and precise enough to assess subtle lameness. However, the technology produced by Tekscan® could possibly be used for objective assessment of gait if the sensors could be modified to record measurements at higher pressure levels. At this point, a new data-logging system was ready for testing with non-trimmable sensors like the mat but designed for use in-shoe on horses. This system was identified as the Equine F-Scan™ system with non-trimmable sensors. In order to test this system, investigators needed to establish an ideal saturation pressure for equine sensors.

CHAPTER 3

3 Design of the new Equine F-Scan™ System

3.1 Introduction

Fuji Prescale pressure-sensitive film has been widely used for in vitro recordings of interface pressures within joints and implants [92, 96-104]. The film is supplied in four grades, defined as “super-low”, “low”, “medium”, and “high” which allow interface pressure measurements between 0.5 and 130MPa to be recorded [92]. The film consists of an active layer of polymer substrate with microscopic colorless bubbles coated on the surface of the substrate (A-film) and a color developing layer (C-film) [91, 92].

On the A-film, the bubbles burst upon application of pressure. The amount of colorless liquid released is dependant on the number of bubbles burst and is thus related to the pressure at a given location. The active layer in the C-film reacts with the colorless liquid and produces a pink stain [92].

The developed film must then be analyzed using standard calibrations based on temperature, humidity and load rate, digital image capture and manipulation techniques to present results as false-color pressure-maps [96].

Knowing how the film worked, investigators suspected that measurements could be taken to estimate the maximum pressures that sensors would need to withstand to determine maximum vertical force from horses at a trot.

3.2 Materials and Methods

Investigators were unsure where the maximum contact pressure values would fall so 3 types of film: low, medium and high were used.

Using one horse assessed as clinically normal, investigators trimmed prescale fuji-film to fit the bottom surface of the hoof. Using a number 2 farrier pad (#2 Flat Pad, Farriers Pride Pads, Farrier Products Distribution, Shelbyville, KY)) trimmed to the size of the hoof, investigators placed the prescale film in contact with the hoof and then placed the farrier pad over the film and taped the film and pad to the hoof wall. Once the film was attached to the hoof, investigators trotted the horse off for 25 m. At this point the film and pad were removed and the film was placed between sheets of parchment paper, rolled up and placed in a cardboard shipping container. The temperature and humidity levels were recorded for processing purposes. The film was processed and analyzed by Sensor Products Incorporated. Each hoof was tested individually and low, medium and high range films were used.

3.3 Results

The low film had a range from 2.4 to 9.65 Megapascals (MPa). The medium film's range was 9.65 to 48.9 MPa and the high film's range was 48.9 to

129 MPa. Forelimb test results indicated that pressure values could reach higher than 129 MPa. Hind limb tests indicated that pressure values were much lower than forelimb pressures and would not exceed 9.65 MPa. The following results show the developed fuji-film with the pressure ranges color-coded. Red indicates high-pressure zones and dark blue represents low-pressure zones. The low range film shows the majority of development in red, indicating pressures near or above the saturation levels for low range film (Figure 21).

Figure 21 – Developed low range prescale fuji-film. Areas developed in blue are representative of pressures in the low range of the film. Areas in red indicate pressures near saturation levels at pressures of 9.65 MPa.

Development of the medium range film showed more than 50% of the development above the saturation pressure of 9.65 MPa (Figure 22), indicating the need for use of the high range film.

Figure 22 – Medium range prescale fuji-film develops in the range of 9.65 MPa to 48.9 MPa. Areas that develop in red indicate pressure saturation levels are being reached on the film.

The high range film developed with less than 10% of the hoof showing pressure higher than 117 MPa (Figure 24). The area of pressure saturation on the high range film indicated that occasionally a small surface area on the hoof could have pressure readings as high as 134 MPa (Figure 23).

Figure 23 – High range prescale Fuji-film develops in the pressure range of 48.9 MPa – 129 MPa. Less than 10% of the film developed red, indicating that pressures can reach up to 134 MPa.

3.4 Conclusions

Based on these results, investigators were confident that pressure ranges from a horse's hoof contacting the ground at the trot could be in the range of 48.9 MPa – 129 MPa. This range was slightly less than the maximum measured at 134 MPa but investigators realized that the film continued to develop more after every hoof strike so the maximum may have been slightly overestimated thereby concluding that the maximum would fall in the high range fuji film.

At this time, Tekscan® was ready to produce a data-logging unit which could be attached to the horse and record measurements from sensors on the horse's hooves. Investigators used sensors made from the same technology as the F-Mat™ system to test this Equine F-Scan™ system. However, it was known that standard sensors designed for human use had a saturation pressure at 0.9 MPa, so the sensors were modified to have a higher saturation pressure at 6.89 MPa. By modifying the sensors so that each sensile saturated at 6.89 MPa, investigators were confident that peak pressures could be measured because the sensile size was 1 mm^2 and the sensors contained at least 2,000 sensiles.

CHAPTER 4

4 Testing the new Equine F-Scan™ System

4.1 Introduction

The design of Tekscan sensors uses two substances such as carbon and copper inlayed in a Mylar substrate in separate sheets to form the sensors. When the two substances come in contact, a measurement of electrical resistance provides the data necessary to calculate the force and pressure values used by investigators. By changing the composition of the substances in the Mylar, Tekscan is able to provide sensors that saturate at different levels. When pressure is applied to the sensors, every connection made between the two substances forms a sense cell and each one of those is capable of measuring pressure up to 6.89 MPa in a 1 mm^2 (Figure 24). This makes this sensor capable of measuring overall pressure up to 134 MPa without saturating because there are over 2,000 sensiles in the sensor. These sensors were non-trimmable and were 51.6 cm^2 (Figure 25).

By testing the F-Mat system against the non-trimmable sensors with higher saturation points and the force platform, investigators could test the accuracy of the new sensors and also show that the saturation of the sensors made a difference in the overall vertical force measurements.

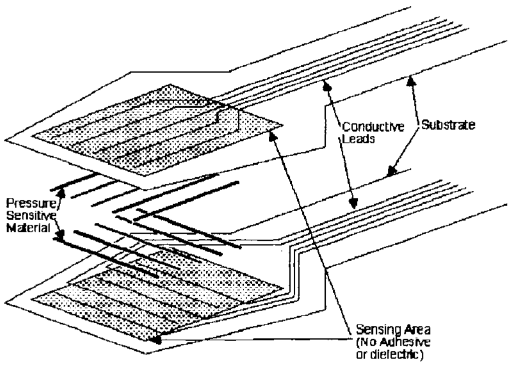


Figure 24 – Diagram of the sensor design. Two sheets of Mylar substrate have substances printed on them. One side with carbon and one with copper. The printed substances are laid together with one page with vertical stripes and one with horizontal striped. When the two substances come in contact a measure of electrical resistivity can be taken.

Figure 25 – Photo of the non-trimmable sensor used with the Equine F-Scan system. Each vertical strip is mirrored on the reverse side with horizontal strips. When pressure is placed on the sensor the two substances come together and form a sense cell with a saturation pressure of 6.89 MPa.

4.2 Materials and Methods

In order to record data with the Equine F-Scan™ system and non-trimmable sensors investigators used a modified Dalric-cuff shoe (Nanric, Inc., Shlebyville, KY) with a #2 farrier pad in the center (Figure 26).

Figure 26 – Modified Dalric-cuff shoe with a #2 farrier pad in the center. The shoe will provide the bottom protective layer for the sensor and allow investigators to attach the sensors with duct tape.

In addition, investigators placed impression material on the sole of the hoof so that any uneven patches of the hoof would be leveled and not give high-pressure readings (Figure 27). Also, another #2 farrier pad was trimmed and placed over the impression material. This was to prevent the impression material from sticking to the sensors (Figure 25). The sensors were then folded and placed inside the shoe, which was placed on the waiting hoof. The bottom surface was left with only one layer of sensor while up on the hoof wall, the folded parts were taped together. By lightly taping the folded sensor parts there was not enough pressure on the sensors to cause pressure readings. The shoe was then taped to the hoof and testing was ready once the cables had been attached to the data-logging unit (Figure 28). In order to attach the sensors to the data-logging unit, the horse had to wear performance boots (Professional's Choice Sports Medicine Products Inc., San Diego, CA) so that the cuff unit, which plugged the sensors into the data-logging unit, could be placed solidly on the horse's leg (Figure 29).

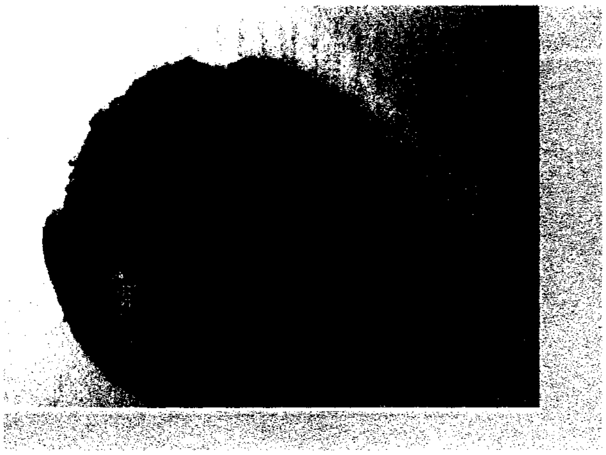


Figure 27. Impression Material. Used to fill uneven or jagged surfaces of the sole, frog and hoof wall prior to testing with nontrimmable sensors.

Figure 28. Performance Boots with the non-trimmable sensors taped on the hoof. The impressions material was placed in along the sole surface. A #2 farrier pad was trimmed to fit the bottom of the hoof and placed over the impression material. The sensors were carefully folded to fit the bottom of the hoof and then the modified Dalric cuff shoe was placed over the sensor. Duct tape was used to attach and keep the shoe and sensors on the hoof.

Figure 29 – Equine F-Scan™ system and sensors on the horse.

Objective Gait Assessment

Two horses were trotted through a chute 15.2 m long and 1 m wide containing the F-Mat™ lying over the force platform (Model 6090-15, Bertec, Inc. Columbus, OH, USA). The horses were trotted at a rate of 2.6 to 3.3 m/s through the infrared laser timers. Data collection continued until 5 whole hoof strikes from each limb had been recorded on the force platform and F-Mat™ and F-Scan™. Measurements were taken with the horses wearing the data-logging unit while trotting over the force platform and mat. The sensors withstood the testing of 2 horses (40 hoof strikes) before the sensor cells were no longer functioning.

Statistical Analysis

The accuracy of each of the Tekscan® systems was tested by running a paired t-test with a comparison of vertical force values from the F-Mat system to the force platform and a comparison of the Equine F-Scan™ System to the force platform. A P-value < 0.05 was considered significant. Coefficients of Variation were also calculated to test the precision of the force plate, F-Mat™ and Equine F-Scan™.

4.3 Results

Results from this test showed the vertical ground reaction force measurements recorded from the force platform and in-shoe system to be very close with the mat system overestimating values (Figure 30).

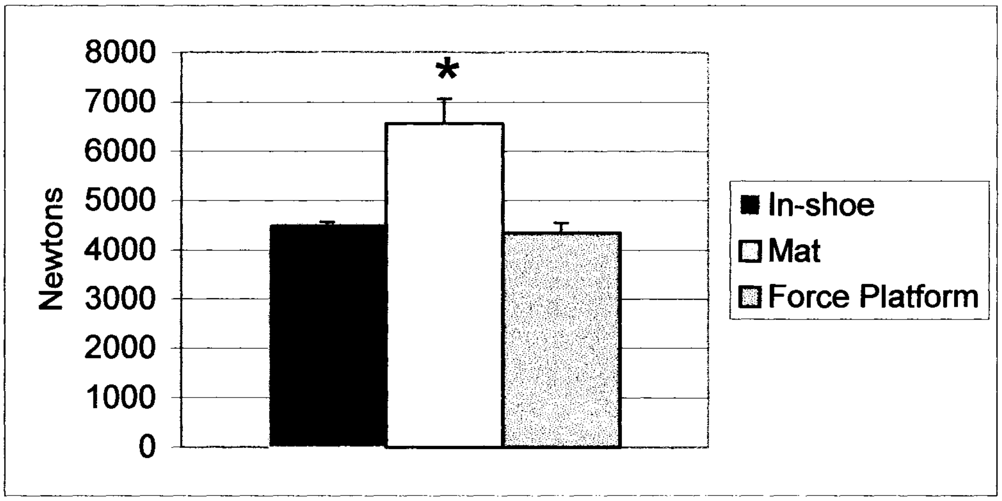
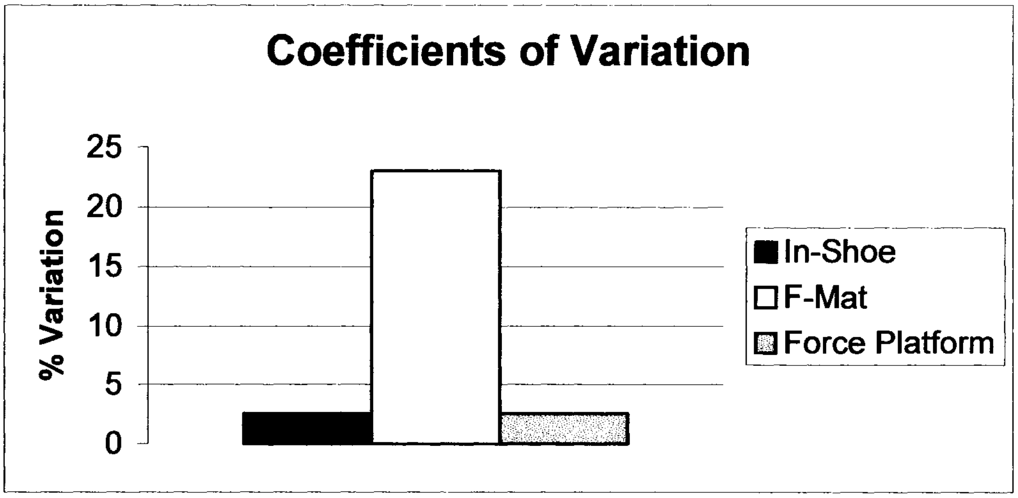


Figure 30. Maximum vertical force values are represented from each testing device. The asterisk represents the significant difference between values from the F-Mat™ and the Force Platform. No significant differences were noted between the Equine F-Scan™ system and the force platform.

In addition the coefficients of variation for vertical force measurements were calculated for each system. Results showed the force platform and in-shoe system to be within acceptable research limits of less than 6-8% while the mat was not as reliable as a research center would expect at 23% (Figure 31).



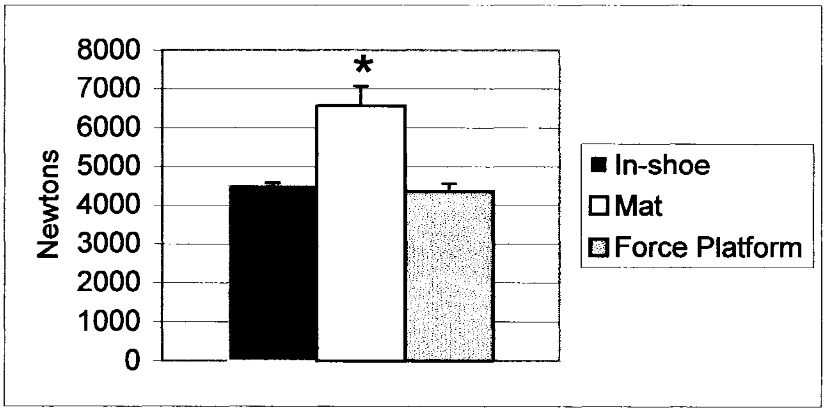


Figure 30. Maximum vertical force values are represented from each testing device. The asterisk represents the significant difference between values from the F-Mat™ and the Force Platform. No significant differences were noted between the Equine F-Scan™ system and the force platform.

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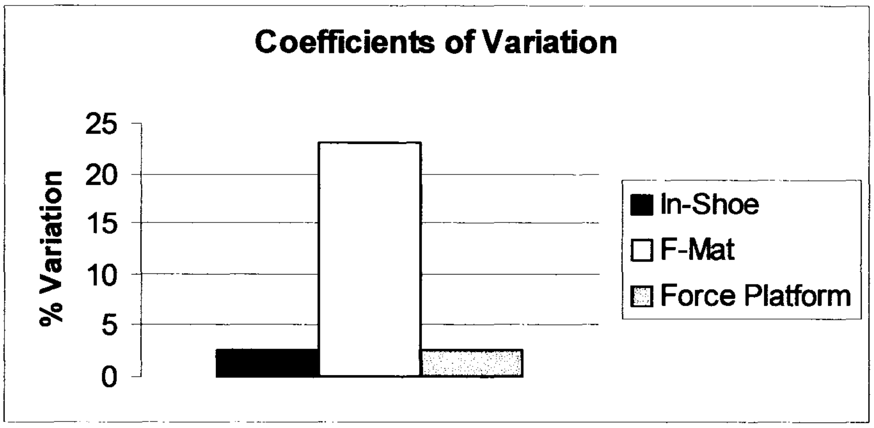

Figure 31 – Graph of the calculated coefficients of variation for the testing of the F-Mat™, Equine F-Scan™ and force platform. Both the force platform and Equine F-Scan™ had calculated coefficients of variation less than 5% while the F-Mat™ had a calculated coefficient of variation of 23%.

4.4 Conclusion

Initial testing of the in-shoe data-logging unit showed investigators that the Equine F-Scan™ system was capable of measuring vertical forces as accurately as the force platform. This indicated to investigators that with the proper sensors, the Equine F-Scan™ system might very well be the pressure measurement system that could be used in the field or in a laboratory setting and provide investigators with accurate and precise quantitative data for gait analysis. The next step was to test the Equine F-Scan™ system with trimmable sensors enabling the investigator to fit sensors to each horse's hoof without the difficulty of folding 51.6 cm^2 sensors into horse-shoes.

Investigators again concluded that the F-Mat™ with sensors that saturate at 0.9 MPa was not accurately measuring vertical ground reaction forces as noted by the overestimated force values seen compared to measured force platform values. This confirmed the thoughts that further testing of the mat was pointless unless new sensors were built into a new mat with higher saturation pressures.

CHAPTER 5

5 Testing the Equine F-Scan System with Trimmable Sensors

5.1 Introduction

The development of a clinician capable of examining equine gait analytically by sight can be difficult. Generally, an individual who has chosen to specialize in the field of equine lameness has spent at least eight years training. During this time, the skills required to identify subtle changes in gait have been developed, training the eye to identify a lameness more subtle than a grade 2 on the AAEP scale which is most often the slightest lameness a common person can identify consistently.

Over the years the examination of locomotion in animals has been aided by the use of noninvasive technology such as videography and force platforms [18]. In human medicine, specifically podiatry, pressure measurement systems have been developed to aid doctors in diagnosis and treatment of foot diseases [75]. Although veterinarians and human doctors may not directly use technology to aid in their evaluations of gait, they very likely will rely on technicians trained to use new technology to aid their diagnoses [18]. As technology advances and veterinarians and researchers look to computers to provide objective data to further supplement their diagnoses, a need for an ideal gait analysis system arises.

The development of the ideal equine gait analysis system may take some time. However, as systems improve, development will continue towards a system that is (1) capable of producing reliable, accurate, reproducible data; (2) sensitive enough to identify subtle changes in gait; (3) capable of refined analysis at high speeds of locomotion; (4) usable without excessive time for equipment setup and calibration; (5) produce results rapidly so the clinician can evaluate techniques; (6) generate sufficient data from which diagnostic decisions can be made; (7) have reasonable operation costs; and (8) not alter the gait patterns of the subject [18].

This paper is a compilation of the testing done on the development of an equine, in-shoe pressure measurement system as an ideal gait analysis system. The goal of the research was to establish the accuracy and precision of the Equine F-Scan System (EFS). To obtain this goal, the EFS was used to record measurements of vertical force to determine if these measurements were precise with little variability and accurate when tested against a force platform.

5.2 Materials and Methods

Animals - Six horses aged 3-20 years weighing 400-550 kilograms were used for this experiment. All procedures were approved by the animal care and use committee.

Calibration Procedures - Prior to testing, the force platform and in-shoe systems were calibrated and checked for proper function.

Force Platform Calibrations - The force platform was set to a recording speed of 1200 Hz, and static weights were loaded onto the plate over a 2 minute interval. Twenty, 23 kg weights were stacked onto the plate until 460 kg was on the plate and settled, then the weights were removed one at a time. The data collected were analyzed for maximum vertical force measurements and verified to the actual vertical force applied as calculated by the equation F=mg (F =force (N), m = mass (kg), g =gravitational acceleration (m/s^2).

EFS Calibration - It has been shown that since the EFS uses individually-activated sensiles, it is best to calibrate the proposed area of activation with a weight(force applied) near the true testing weight range [73]. Each of the 6 horses being tested was also placed standing with both front limbs on the force platform and measurements were recorded. Investigators then lifted one of the front limbs and took recordings again. The process was later repeated for each hind limb. From the vertical force measurements recorded, the mass of the horse through the limb on the plate was determined by dividing the total vertical force recorded by gravitational acceleration. This process provided investigators with a method for calibrating the sensors after being trimmed and placed on the horse. Calibration of the EFS was accomplished by setting the software package to a calibration load of the calculated mass, which was assumed to be the actual mass born by each limb according to force platform measurements. At that point, the opposite front or hind limb from the limb with the sensor was picked up and that sensor was calibrated. Each hoof was calibrated in this manner.

Data Acquisition - In order to attach the trimmable sensors to the hoof, investigators used a modified Davis Barrier boot (Davis Manufacturing, Brandon, WI, USA) (Figure 32). The sensor was trimmed to fit the foot and placed between a farrier pad and the barrier boot. Impression material was placed against the sole of the hoof to fill in any rough surfaces. Then a #2 farrier pad was trimmed and placed over the impression material. The sensor was then trimmed to fit and placed against the farrier pad (Figure 33 & 34). The barrier boot was placed over the impression material, farrier pad and sensor and placed on the horse's hoof. The sensors were attached to a data-logging unit on the horse's back and this unit recorded contact on the sensors during each recording phase. This allowed recording without being attached to a computer, making this system mobile and capable of recording measurements from all four limbs at the same time at a rate of 127 Hz.

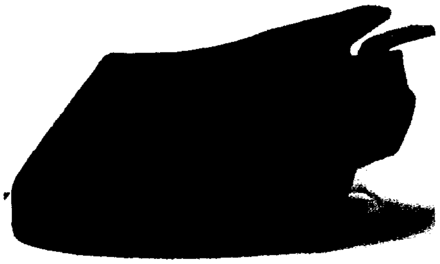

Figure 32 – A modified Davis Barrier Boot. The bottom shoe of rubber has been removed leaving only the boot for attachment to the hoof.

Figure 33 – Trimmable sensor before trimming to fit the hoof. The sensors are 339 cm^2 with 1089 sense cells.

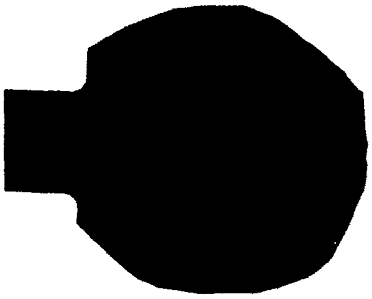

Figure 34 – Sensor trimmed to fit the horse's hoof.

The horses were trotted across a force platform, while wearing the EFS with trimmable sensors. The force platform was set in concrete and infrared timers were placed 3 m apart, equidistant from the force platform, for standardization of horse speed (Figure 35). The horses were trotted across the force platform while wearing the EFS at a rate of 2.6 to 3.3 m/s. The recording speed of the force platform was set at 1,200 Hz and the EFS at 127 Hz. Measurements were taken until 5 strikes from each hoof were collected or until the trimmable sensors would no longer take measurements. On average, four measurements were recorded from each hoof. The trimmable sensors were sensitive to wear after trimming. Once trimmed, the edges of the two layers of the sensors were no longer laminated together, so it appeared that twisting on the sensor when the horse changed direction may have caused stress on the layers of plastic, prematurely removing the ink and therefore making the sensors stop working.

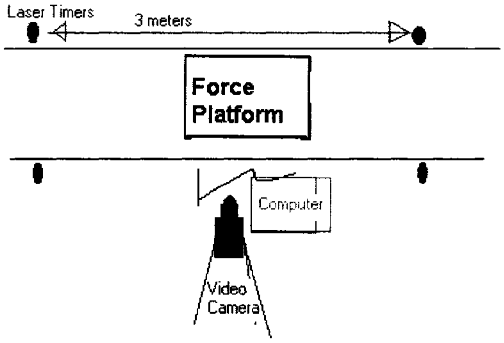

Figure 35. Diagram of the data collection setup. The horses travel across a mat with a handler. Random hooves land on the force platform. Deformation of the plate causes a production of electricity measured by a computer and further calculated into forces. The video camera records which hoof strikes the platform and mat.

From this data, measurements of maximum vertical force during the stance phase were analyzed for differences between measuring devices and changes from one data collection to the next. This design allowed researchers to test the EFS against the force platform by only testing the hooves that landed on the force platform.

Statistical Analysis - The data were analyzed for vertical force readings. The force platform is widely recognized as a tool capable of providing objective measurements for assessment of lameness and in this case is to be the standard tested against. Therefore, the accuracy of the EFS system was tested based on the definition of accuracy as deviating slightly or within acceptable limits from a standard. To test the accuracy of the EFS, measurements from the pressure system were compared to the force platform. The mean values of the maximum force from each instrument were compared to each other using paired t-tests with significant differences noted when $P < 0.05$.

Investigators also used the Bland-Altman test to assess agreement between measurement devices [95]. The amount of agreement is defined by how close the points lie to the line of equality which is a line that all points from both devices would lie on if the two systems gave exactly the same reading every time. By using this approach of measuring agreement, investigators compared the accuracy of measurements from the EFS against force platform measurements. In order to test for lack of agreement, the average vertical force from the stance phase was calculated for both systems. This is the average value calculated from all maximum vertical force measurements from each system. Then the difference between vertical force measurements between the force platform and EFS were calculated. The difference in vertical force measurements between systems was plotted against the average of the two systems. If there was no obvious relation between the difference and the mean, then the bias was calculated. The bias is estimated by the mean difference and the standard deviation of the differences. If there was a bias it was adjusted by subtracting the mean difference from vertical force measurements from the EFS. Differences in vertical force measurements between the two systems would be expected to be between the mean of the two systems and +/- 2 standard deviations of the differences, referred to as the "limits of agreement". If the range of the differences was small enough, in this case less than 1,000 N, then a subtle lameness could be detected and the pressure system could replace the force platform or the two can be used interchangeably. One Thousand Newtons was determined to be an acceptable cutoff after reviewing work from Seeherman et al. (1987) in which a force platform was used to take measurements prior to and after a lameness in the front limb had been induced [52].

The precision of both systems was monitored because precision is defined by a system that is capable of measurement that is successively repeated within close specified limits. Precision was monitored by calculating the coefficient of variation (COV). The COV was calculated in SAS (Statistical Analysis System, Cary, NC, USA) for each system to test the variability of measurements from each individual system from the recorded maximum vertical force measurements from each system. The COV from each system needed to be below 8% in order to prove to investigators that the systems were capable of assessing subtle lameness. For research purposes, we felt that a COV of < 8% was essential for this line of work. Using the Bland-Altman test again, the precision of the estimated limits of agreement were then calculated to show whether the previous calculations show good or bad agreement by monitoring the calculated standard errors, bias and 95% confidence intervals to test the precision of the measurements [95]. If the intervals were wide, there can be considerable variation between the differences in vertical force measurements from the two systems and the degree of agreement is not acceptable. In this case, a standard vertical force measurement would be between 3,500 N and 5,000 N. Therefore, confidence intervals with ranges up to 1,000 N would indicate variations in measurements of up to 25%, indicating a less than acceptable degree of agreement. Finally a correlation was calculated with the dependent variable as maximum vertical force measurements from the EFS and independent variable as maximum vertical force measurements from the force platform in SAS to check for a linear relationship between the measurement systems and test the accuracy of the EFS. The correlation coefficient was calculated between the force platform and EFS.

5.3 Results

The accuracy of the force platform was checked using static weights. The weights were placed on the force platform and measurements were taken. With 460 kg of weight on the platform, the readings did not vary by more than 4.6 kg (1.0%).

Dynamic testing of the accuracy of the EFS system was determined by analysis of the vertical force measurements from both systems. Data were checked for normality and a paired t-test for means was conducted to test the accuracy (Figure 36) of the EFS when tested against measurements from the force platform. No significant differences were noted between the force platform and the EFS (p=0.294).

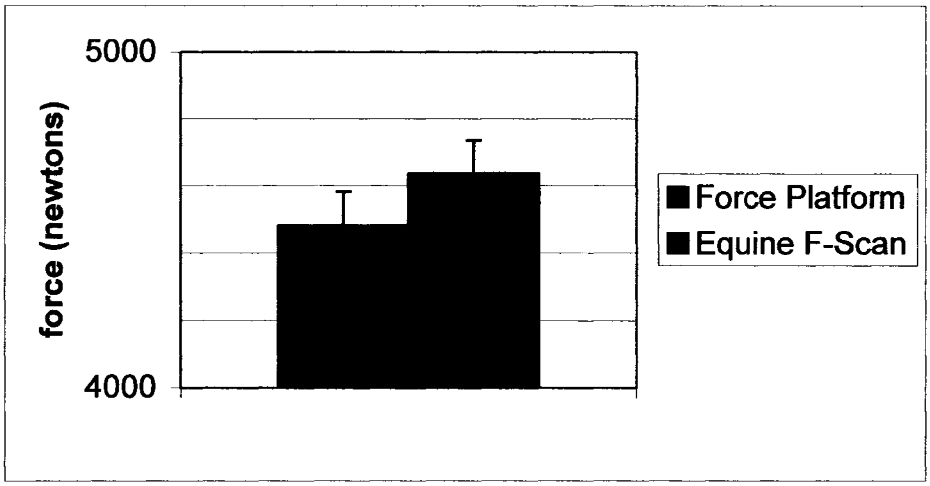

Figure 36. Average of the peak vertical forces during the stance phase from each system with standard deviation bars included (p=0.294).

When assessing measuring agreement, the standard scatter plot of results of one measuring method against those of the other tell very little (Figure 37). The data points are all clustered close together near the line making assessment of between-method differences difficult.

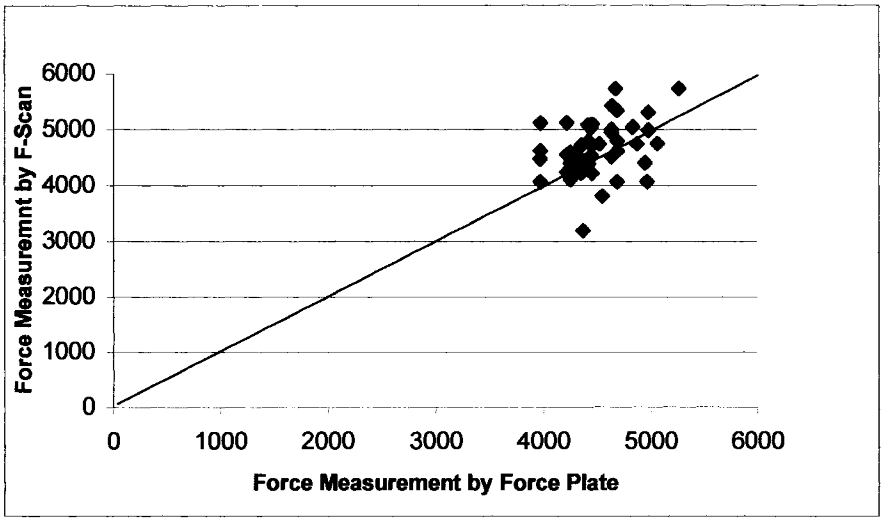

Figure 37 – A scatter plot of the force measurements with a line of equality, showing a cluster of data points.

Examination of the plotted data of the difference between the methods against their mean (Figure 38) showed there was no obvious relationship between the mean and the difference due to the large discrepancies between devices of up to 1,200 N. The limits of agreement were –1225 N to 915 N (Figure 38). The mean value was plotted at (4416,0). The values plotted for differences between devices show the error of the EFS system compared to measurements from the force platform. With a range that large, there is a lack of agreement between the systems.

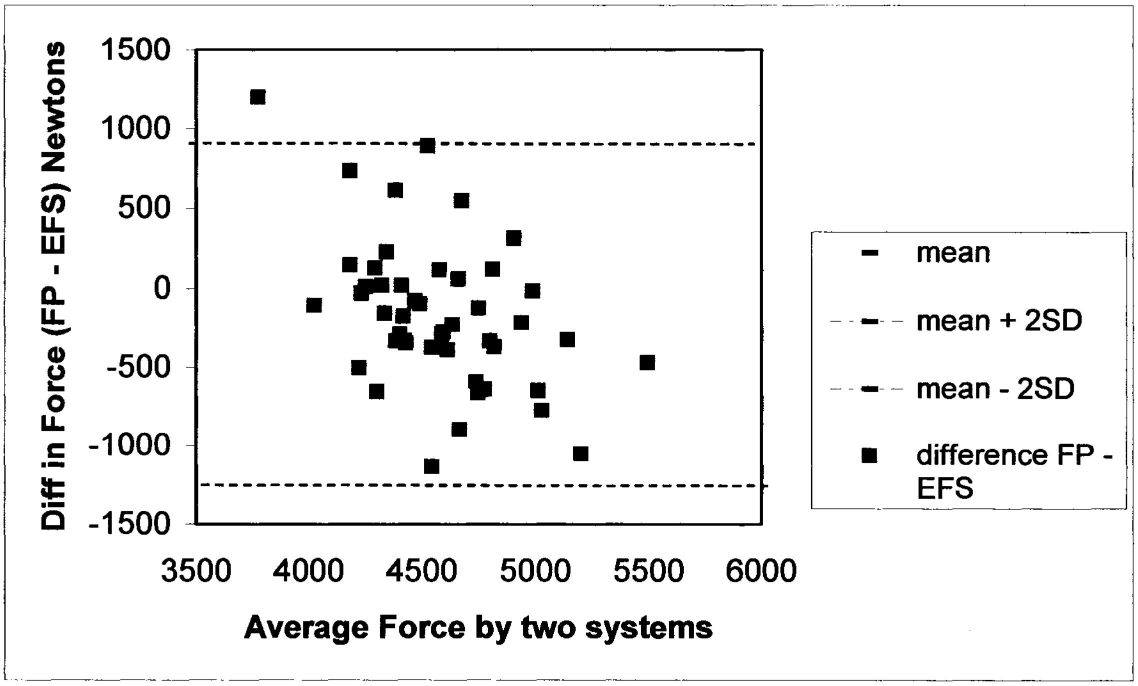

Figure 38. Differences in force measurements plotted against mean vertical force measurement data from the force platform and EFS. This plot allows investigators to observe any possible relationship between the measurement error and the true value. The limits of agreement were marked by dashed black lines at 915 and -1224.

Results from analysis of vertical force measurements were used to assess the precision of both systems. Coefficients of variation were calculated for each system using recorded maximum vertical force measurements from each system. Results indicated a COV at 6.6% for the force platform and 10.2% for the EFS (Figure 39).

The precision of the system was also tested using the Bland-Altman test Figure 40). The mean of the differences should measure within the limits of –284 N to –25 N, (95% Confidence Interval (CI) when measurements were compared between the force platform and EFS. The calculated mean of the difference was –155 N, which falls within the calculated range. Therefore, that means 95% of the time, there was a difference between the measurements of an average of

155 N. In addition the upper limits of agreement should be in the range of 691 N to 1139 N (CI), and the calculated upper limit was 915 N. The lower limits should be in the range of –1449 N to –100 N (CI) and the calculated lower limit was –1225 N. Although the calculated mean, upper and lower limits were within the 95% CI, the range of the intervals was large, reflecting great variation between the two systems, and a small sample size, indicating a lack of precision in measurements from the EFS and therefore a less than acceptable degree of agreement.

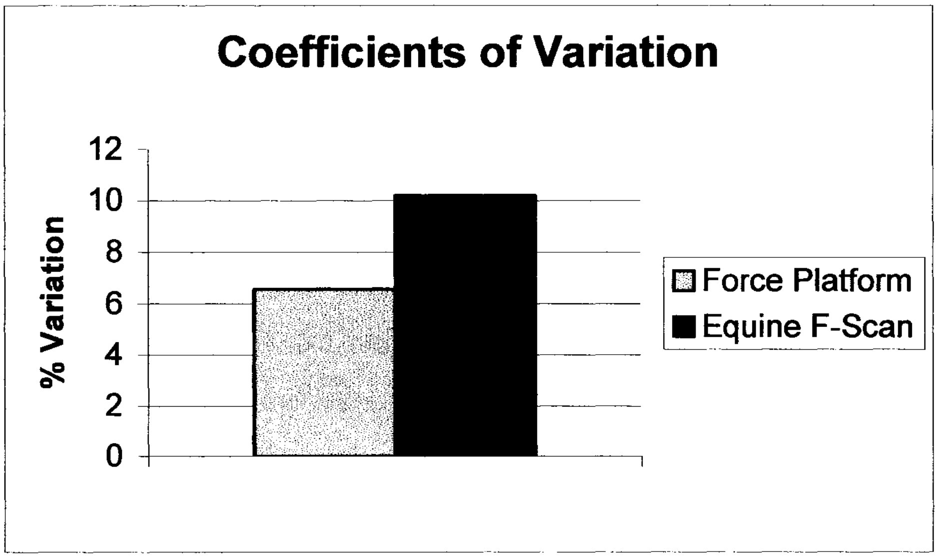

Figure 39 – Graphical representation of the coefficients of variation show that the Force platform with a value less than 8% is the only one of the systems that produced data precise enough for use in research.

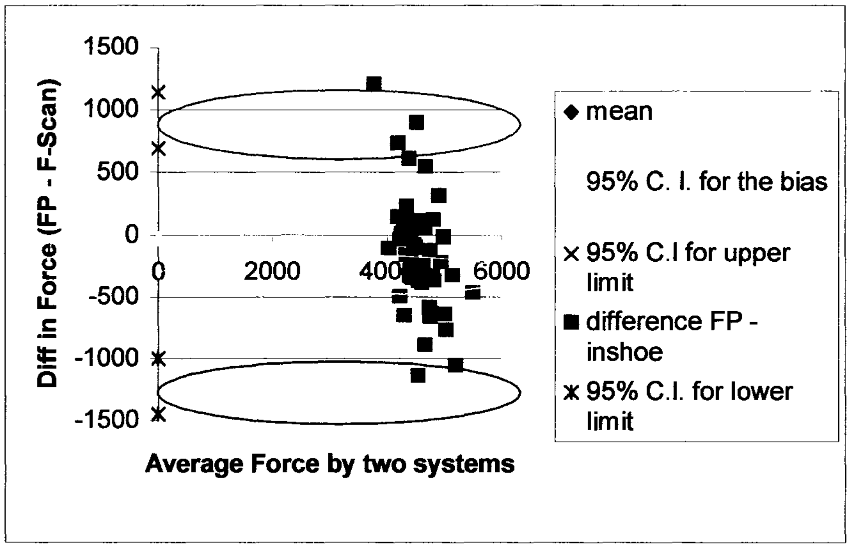

Figure 40 – Differences against mean for vertical force data with 95% confidence intervals for the limits of agreement, and bias marked with ellipses for the range of the interval. Teal represents the upper 95% CI limits, yellow is the 95% CI for the bias and navy is the lower 95% CI limits.

A correlation was calculated to test for the linear relationship between force measurements from the EFS and force platform systems (Figure 41). The R-Square value was 0.1326. This indicates that only 13% of the variability in force measurements from the EFS is associated with the straight line of force measurements from the force platform. Additionally, the calculated coefficient of correlation between measurements from the two systems is 0.3641. Controlling for risk at alpha = 0.05 the critical value for n = 50 is 0.977. The fact that the calculated coefficient of correlation does not exceed 0.977 helps to support the conclusion that the distribution of error departs from a normal distribution.

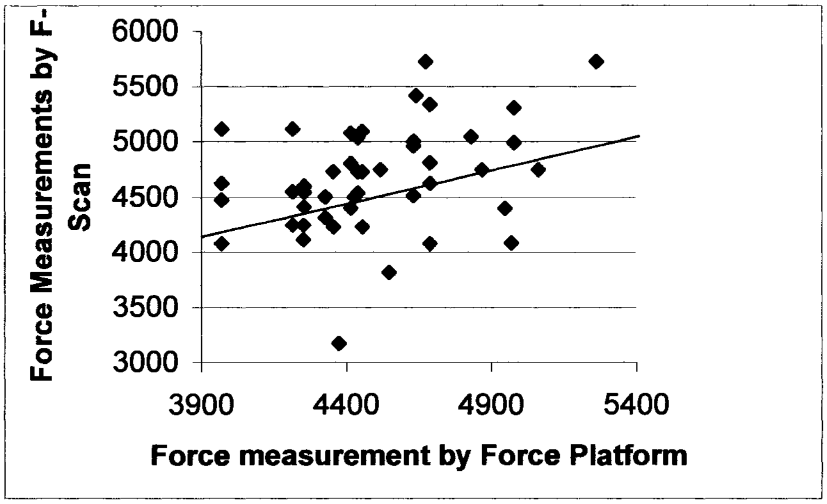

Figure 41 – Scatter Plot of force measurements from the F-Scan™ versus the F-Mat™ with a regression line from the equation F-Scan Force = 2007.8 + .58645*(F-Plate Force). The R-Square value = 0.1326. The coefficient of correlation between F-Scan™ and F-Plate measurements = 0.3641.

5.4 Conclusions

Testing of the EFS with trimmable sensors showed investigators that this system was less precise than testing the EFS with non-trimmable sensors. The coefficient of variation for the EFS with trimmable sensors was 10.4% while the non-trimmable sensors was 2.6%. Several factors may have affected the overall measurements, (1) more horses were tested with the trimmable sensors so the potential for differences in variability were higher, (2) investigators used a modified Davis Barrier Boot to attach the sensors to the hoof, rather than a modified Dalric cuff shoe and tape. This change in application of the sensor may have allowed the sensor to move more under the hoof potentially increasing variability. Also, the additional layer of rubber between the sensor and testing surface may change measurements by the sensor due to the rubber absorbing some of the force.

The accuracy of the EFS tested against the force platform indicated there was not a significant difference between measurements, so the EFS may be as accurate as the force platform. However, the correlation tests showed very little relationship between the measurements from the EFS and the force platform, indicating that there is some indication that at least one set of measurements deviates from a normal distribution and therefore a linear relationship with the other measurement system. In addition, the test for measuring agreement showed a large difference in measurements making investigators conclude there was a basic lack of agreement between the two systems. This indicated the EFS potentially may not be able to detect subtle changes in gait but if variability could be reduced the systems precision may be improved making it as precise and accurate as the force platform. Further experiments to test if reductions in variability indeed improve the precision of the EFS need to be done. Investigators have determined from testing that the trimmable EFS is capable of measuring vertical forces. However, the key to making this system precise enough to be used in place of a force platform for objective assessment of gait is in the attachment of the sensors to the hoof. Further work needs to be done to establish a method that keeps the sensors from moving but does not require extensive attachment time. Originally investigators used a modified Dalric cuff shoe duct taped over impression material and the bottom surface of the hoof. However, this method of attachment was time consuming, so investigators attempted the use of a modified Davis barrier boot to lessen the attachment time necessary for the EFS. After testing the barrier boot, investigators realized that although the boot was easier to attach, the rubber did not conform tight enough to the hoof wall and when the horses changed direction, the boot shifted, twisting the sensors and interfering with the movement of the horse. This twisting caused premature wear on the sensors and decreased the life of the disposable sensors. Also, investigators suspected that the extra layer of rubber under the hoof was causing an increase in the variability of the force platform and EFS measurements as well. The premature wear made the sensors not cost effective and investigators suspected that some of the increase in variation between testing non-trimmable and trimmable sensors was in part due to the attachment with the barrier boot.

Another potential problem area with the EFS was attachment of the sensors to the data-logging unit. From the beginning of testing the EFS, investigators had difficulty keeping the cords from the sensors attached. The cords are a potential problem area with this system, because if the cords become unattached during testing, none of the measurements can be downloaded from the data-logging unit and the test is a failure. This leads to excessive wear on the sensors, potentially causing the sensors not to be precise or accurate enough for use in research. Secondly, this makes the system not cost or time effective and not user-friendly. There is also potential for the dangling cords to affect the movement of the horse and change overall vertical force measurements. Further development of the EFS from a data-logging unit to a telemetry unit will aid investigators with the problems caused by cords attaching the sensors to the data-logging unit. Investigators believe changing the mode of attachment and using a telemetry unit instead of a data-logging unit will make this system usable as an accurate and precise gait analysis system.

After modifications of the EFS are completed, these changes should improve the ability of the system to measure vertical force more precisely. When the ability of the system to accurately and precisely measure vertical force has been established, investigators will need to further assess the system as a potential tool when assessing lameness. In order to do this, investigators will need to test the ability of the system to detect lameness by using horses that are lame for testing. The accuracy of the current system was not in question but the precision of it was. If the precision of the system is improved, the system may be capable of detecting subtle lameness in horses and accomplishing one of the goals of investigators which was to find a gait analysis system that is capable of assessing lameness, while being user-friendly, relatively inexpensive and usable in both a research and clinical setting.

Investigators have concluded that the F-Mat system designed for humans is incapable of measuring vertical force accurate and precise enough to be used as a tool for objectively measuring lameness. However, a change in sensor specifications may allow the F-Mat system to be capable of accurately and precisely recording vertical force measurements. Investigators know this from testing the non-trimmable sensors with the EFS system. Results from testing these sensors, showed that when properly designed for high-pressure saturations, the technology behind the sensors could be used in a mat design that could be used as a tool for objectively measuring lameness. The non-trimmable sensors were a trimmed down version of the mat sensors allowing investigators to use them in-shoe rather than in a platform setup. Because the precision of the EFS with non-trimmable sensors tested with only 2.6% variation in measurements, investigators concluded the technology could be used in a mat and produce data precise enough for use in research.

Further testing of the force platform will allow investigators to establish the ability of the system to objectively assess lameness and provide a standard to continue to test other systems against. The precision of the force platform can be improved upon also. Investigators know that the speed the horse is trotting at affects the variability of measurements. In addition investigators suspect that other environmental factors influence the variability of measurements. Further investigation into a handler affect needs to be done to conclude how much influence the handler of the test subject has on overall variability and overall force measurements. Investigators suspect that handler can influence vertical force measurements by pulling on the lead as the horses are moving across the force platform. This would change overall vertical force measurements and influence the ability of investigators to use data from the force platform to assess subtle lamenesses in the horse. However, it is still unclear whether or not handler affects variability in measurements. Other factors to be looked at include temperature at testing time and whether or not cold or excessive heat change electrical impulses produced by the force platform. Further testing of these factors and other issues that arise will make the force platform a true gold standard in the field of gait assessment.

References

1. Perino, V.V., *The Tekscan System: A Tool for Objectively Measuring Lameness in the Horse*, in *MS Thesis*. 2002, Fort Collins, CO: Colorado State University. p. 1-60.
2. *Definition and classification of lameness. In Guide for veterinary service and judging of equestrian events.* 1991: p. 19.
3. Weishaupt, M.A., Wiestner, T., Hogg, H.P., Jordan, P., Auer, J.A., Barrey, E., *Assessment of gait irregularities in the horse: eye vs. gait analysis.* Equine Veterinary Journal Supplement, 2001. 33: p. 135-140.
4. Caron, J.P., *Objective and Subjective Gait Analysis Techniques*, in *Current techniques in equine surgery & lameness*, M.J. White NA, Editor. 1998, WB Saunders Co.: Philadelphia, PA. p. 501-504.
5. Jeffcott, L.B., Rossdale, P.D., Freestone, J., Frank, C.J., Towers-Clark, P.F., *An assessment of wastage in thoroughbred racing from conception to 4 years of age.* Equine Vet J, 1982. 14: p. 185-198.
6. USDA, *Lameness and Laminitis in U.S. Horses*, in *USDA:Aphis:VS,CEAH, National Animal Health Monitoring System.* 2000: Fort Collins, CO. p. 1-6.
7. www.igha.com/equids02.html.
8. Leach, D.H., Dagg, A.I., *A review of research on equine locomotion and biomechanics.* Equine Veterinary Journal, 1983. 15: p. 93-102.
9. Zahedi, M.S., Spence, W.D., Solomonidis, E., Paul, J.P., *Repeatability of kinetic and kinematic measurements in gait studies of the lowerlimb amputee.* Prosthes Orthot. Int., 1987. 11: p. 55-64.
10. Barrey, E., *Methods, Applications and Limitations of Gait Analysis in Horses.* Vet J, 1999. 157: p. 7-22.
11. Stashak, T.S., *Horseowner's guide to lameness.* 1995, Media: Williams and Wilkins.
12. Clayton, H.M., *Instrumentation & techniques in locomotion and lameness.* Vet Clin North Am. Equine Practice, 1996. 12(2): p. 337-350.
13. Leach, D.H., Ormrod, K., Clayton, H.M., *Standardised terminology for the description and analysis of equine locomotion.* Equine Vet J, 1984. 16(6): p. 522-528.
14. Anonymous, *Definition and classification of lameness. In Guide for veterinary service and judging of equestrian events.* 1991: p. 19.
15. Ross, M.W., Dyson, S. J., *Diagnosis & Management of Lameness in the Horse.* 2003, Saunders: St. Louis, Missouri. p. 213-222.
16. Clayton, H.M., *Advances in motion analysis.* Vet Clin North Am - Equine Practice, 1991. 7(2): p. 365-382.

17. Welsh, E.M., Gettinby, G., Nolan, A.M., *Comparison of a visual analogue scale and a numerical rating scale for assessment of lameness, using sheep as a model.* AM J Vet Res, 1993. 54(6): p. 976-983.
18. Leach, D., *Noninvasive technology for assessment of equine locomotion In Lameness in Equine Practice.* 1993, Trenton, NJ: Veterinary Learning Systems. 180-190.
19. Keegan, K.G., Wilson, D.A., Wilson, D.J., Smith, B., et al., *Evaluation of mild lameness in horses trotting on a treadmill by clinicians and interns or residents and correlation of their assessments with kinetic gait analysis.* American J Vet Res., 1998. 59(11): p. 1370-77.
20. Back, W., Barnevald, A., can Weeren, P.R., van den Bogert, A.J., *Kinematic Gait Analysis in Equine Carpal Lameness.* Acta Anat., 1993. 146: p. 86-89.
21. Buchner, H.H.F., Savelberg, H.H.C.M., Schamhardt, H.C., Barnevald, A., *Bilateral lameness in horses - A kinematic study.* The Veterinary Quarterly, 1995. 17: p. 103-105.
22. Peham, C., Licka, T., Girtler, D., Scheidl, M., *Supporting forelimb lameness: clinical judgement vs. computerized symmetry measurement.* Equine Vet J, 1999. 31(5): p. 417-21.
23. Peham, C., Licka, T., Girtler, D., Scheidl, M., *Hindlimb lameness: clinical judgement versus computerized symmetry measurement.* The Veterinary Record, 2001(June 16, 2001): p. 750-752.
24. Keegan, K.G., Yonezawa, Y., Frank Pai, P., Wilson, D.A., *Accelerometer-based system for the detection of lameness in horses.* Biomedical Sciences Instrumentation, 2002. 38: p. 107-112.
25. Riemersma, D.J., Van den Bogert, A.J., Jansen, M.O., Schamhardt, J.C., *Influence of shoeing on ground reaction forces and tendon strains in the forelimb of ponies.* 1996. 28(2): p. 126-132.
26. Biewener, A.A., Thomason, J., Goodship, A., Lanyon, L.E., *Bone stress in the horse forelimb during locomotion at different gaits: A comparison of two experimental methods.* J. Biomechanics, 1983. 16(8): p. 565-76.
27. Savelberg, H.H.C.M., Van Loon, T., Schamhardt, H.C., *Ground reaction forces in horses. Assessed from hoof wall deformation using artificial neural networks.* Equine Vet J Supplement, 1997. 23: p. 6-8.
28. Bontrager, E.L., *Instrumented gait analysis systems.* Gait Analysis in the Science of Rehabilitation. Vol. 2. 1998, Washington, DC: Department of Veteran Affairs. 11-32.
29. Anderson, M.A., Mann, F.A., *Force Plate Analysis: A noninvasive tool for gait evaluation.* Sm Animal Orthopedics, 1994. 16(7): p. 857-864.
30. Budsberg, S.C., Verstraete, M.C., Soutas-Little, R.W., *Force plate analysis of the walking gait in healthy dogs.* AM J Vet Res, 1987. 48: p. 915-918.
31. Yanoff, S.R., Hulse, D.A., Hogan, H.A., *Measurements of vertical ground reaction forces in jumping dogs.* Vet Comp Ortho Trauma, 1992. 5: p. 44-50.
32. Jevens, D.J., Hauptman, J.G., DeCamp, C.E., *Contributions to variance in force-plate analysis of gait in dogs.* AM J Vet Res, 1993. 53: p. 612-615.

33. Riggs, C.M., DeCamp, C.E., Soutas-Little, R.W., Richter, M.A., *Effects of subject velocity on force plate measured ground reaction forces in healthy greyhounds at the trot.* AM J Vet Res, 1993. 54(9): p. 1523-1526.
34. Budsberg, S.C., Jevens, D.J., Brown, J.B., *Evaluation of limb symmetry indices, using ground reaction forces in healthy dogs.* AM J Vet Res, 1997. 54(9): p. 1569-1574.
35. Roush, J.K., McLaughlin, R.M., *Effects of subject stance time and velocity on the ground reaction forces in clinically normal greyhounds at the walk.* AM J Vet Res, 1994. 55(12): p. 1672-1676.
36. McLaughlin, R.M., Roush, J.K., *Effects of subject stance time and velocity on the ground reaction forces in clinically normal greyhounds at the trot.* AM J Vet Res, 1994. 55(12): p. 1666-1671.
37. Rumph, P.F., Lander, J.E., Kincaid, S.A., *Ground reaction force profiles from force platform gait analysis of clinically normal mesomorphic dogs at the trot.* AM J Vet Res, 1994. 55: p. 756-761.
38. Budsberg, S.C., Verstraete, M.C., Brown, J., *Vertical loading rates in clinically normal dogs at a trot.* AM J Vet Res, 1995. 56: p. 1275-1279.
39. McLaughlin, R.M., Roush, J.K., *Effects of increasing velocity on braking and propulsion times during force plate analysis in greyhounds.* AM J Vet Res, 1995. 56: p. 159-161.
40. Cross, A.R., Budsberg, S.C., Keefe, T.J., *Kinetic gait analysis assessment of meloxicam efficacy in a sodium urate-induced synovitis model in dogs.* AM J Vet Res, 1997. 58(6): p. 626-631.
41. Deuland, R., Bartel, D.L., Antonson, E., *Force-plate techniques for canine gait analysis of total hip and excision arthroplasty.* J Am Anim Hosp Assoc, 1978. 13: p. 547-552.
42. Budsberg, S.C., Verstraete, M.C., Soutas-Little, R.W., *Force plate analysis before and after stabalization of canine stifles for cruciate injury.* AM J Vet Res, 1988. 49: p. 1522-1524.
43. McLaughlin, R.M., Miller, C.W., Taves, C.L., *Force-plate analysis of triple pelvic osteotomy for the treatment of canin hip dysplasia.* Vet Surg, 1991. 20: p. 291-297.
44. Griffon, D.J., McLaughlin, R.M., Roush, J.K., *Vertical ground reaction force distribution during experimentally induced shoulder lameness in dogs.* Vet Comp Ortho Trauma, 1994. 7: p. 154-157.
45. Rumph, P.F., Kincaid, S.A., Visco, D.M., Baird, D.K., Kammermann, J.R., West, M.S., *Redistrubition of vertical ground reaction force in dogs with experimentally induced chronic hindlimb lameness.* Vet Surg, 1995. 24: p. 384-389.
46. Muir, P., Markel, M.D., Bogdanske, J.J., *Dual-energy X-ray absorptiometry and force-plate analysis of gait in dogs with healed femora after leg lengthening plate fixation.* Vet Surg, 1995. 24: p. 15-24.
47. McLaughlin, R.M., Roush, J.K., *A comparison of two surgical approaches to the scapulohumeral joint in dogs.* Vet Surg, 1995. 24: p. 207-214.
48. Vasseur, P.B., Johnson, A.L., Budsberg, S.C., *Randomized, controlled trial of efficacy of carprofen, a nonsteroidal anti-inflammatory drug, in the*

treatment of osteoarthritis in dogs. J AM Vet Med Assoc, 1995. 206: p. 807-811.

49. Smidt, G.L., Wadworth, J.B., *Floor reaction forces during gait: comparison of patients with hip disease and normal subjects.* Phys Ther, 1973. 53: p. 1056-1062.
50. Stauffer, R.N., Chaos, E.Y.S., Gyory, A.N., *Biomechanical gait analysis of the diseased knee joint.* Clin Orthop, 1977. 126: p. 246-255.
51. Andriacchi, T.P., Ogle, J.A., Galante, J.O., *Walking speed as a basis for normal and abnormal gait measurements.* J Biomech, 1977. 10: p. 261-268.
52. Seeherman, H.J., Morris, E.A., Fackelman, G.E., *Computerized force plate determination of equine weightbearing profiles.* Equine Exercise Physiology, 1987. 2: p. 537-552.
53. Merkens, H.W., Schamhardt, H.C., Kersjes, A.W., *Ground reaction force patterns of Dutch warmblood horses at normal walk.* Equine Vet J, 1985. 18(3): p. 207-214.
54. Pratt, G.W., Jr., O'Connor, J.T., Jr., *Force plate studies of equine biomechanics.* AM J Vet Res, 1976. 37(11): p. 1251-1255.
55. Schryver, H.F., Bartel, D.L., Langrana, N., Lowe, J.E., *Locomotion in the horse: Kinematics and external and internal forces in the normal equine digit in the walk and trot.* AM J Vet Res, 1978. 39(11): p. 1728-1733.
56. Gingerich, D.A., Auer, J.A., Fackelman, G.E., *Force plate studies on the effect of exogenous hyaluronic acid on joint function in equine arthritis.* J Vet Pharmacol Therap, 1979. 2: p. 291-298.
57. Winter, D.A., *The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological.* 2nd edn ed. 1990, Waterloo: University of Waterloo Press.
58. Colborne, G.R., Lanovaz, J.L., Sprigings, E.J., Schamhardt, H.C., Clayton, H.M., *Joint moments and power in equine gait: a preliminary study.* Equine Vet J Supplement, 1997. 23: p. 33-36.
59. Clayton, H.M., Hodson, E.F., Lanovaz, J.L., Colborne, G.R., *The hindlimb in walking horses: 2. Net joint moments and joint powers.* Equine Vet J, 2001. 33(1): p. 44-48.
60. Clayton, H.M., Schamhardt, H.C., Lanovaz, J.L., Colborne, G.R., Willemen, M.A., *Net joint moments and joint powers in horses with superficial digital flexor tendinitis.* AM J Vet Res, 2000. 61: p. 197-201.
61. Clayton, H.M., Hodson, E.F., Lanovaz, J.L., *The forelimb in walking horses: 2. Net joint moments and joint powers.* Equine Vet J, 2000. 32: p. 295-300.
62. Clayton, H.M., Lanovaz, J.L., Schamhardt, H.C., Willemen, M.A., Colborne, G.R., *Net joint moments and powers in the equine forelimb during the stance phase of the trot.* Equine Vet J, 1998. 30: p. 384-389.
63. Lanovaz, J.L., Clayton, H.M., Colborne, G.R., Schamhardt, H.C., *Forelimb kinematics and joint moments during the swing phase of the trot.* Equine Vet J, 1999. 30: p. 235-239.

64. Merkens, H.W., Schamhardt, H.C., *Distribution of ground reaction forces of the concurrently loaded limbs of the Dutch warmblood horse at the normal walk.* Equine Vet J, 1988. 20(3): p. 209-213.
65. Dow, S.M., Leendertz, J.A., Silver, I.A., Goodship, A.E., *Identification of subclinical tendon injury from ground force reaction analysis.* Equine Vet J, 1991. 23(4): p. 266-272.
66. Bjorck, G., *Studies on the draight forces of horses: Development of a method using strain gauges for measuring forces between hoof and ground.* Acta Agric Scan., 1958. 8(4).
67. Barrey, E., *Investigation of the vertical hoof force distribution in the equine forelimb with an instrumented horseboot.* Equine Vet J Supplement, 1990. 9: p. 35-38.
68. Kai, M., Aoki, O., Hiraga, A., Oki, H., Tokuriki, M., *Use of an instrument sandwiched between the hoof and shoe to measure vertical ground reaction forces and three-dimensional acceleration at the walk, trot, and canter in horses.* AM J Vet Res, 2000. 61(8): p. 979-85.
69. Frederick, E.C., Hartner, K.P., *The evolution of foot pressure measurements.* Sensors, 1993: p. 30-35.
70. Alexander, I.J., Chao, E.Y.S., Johnson, K.A., *The assessment of dynamic foot-to-ground contact forces and plantar pressure distribution: A review of the evolution of current techniques and clinical applications.* Foot and Ankle, 1990. 11(3): p. 152-167.
71. Donaghue, V.M., Veves, A., *Foot pressure Measurement.* Orthop Phys Ther Clin N Am, 1997. 6(1): p. 1-16.
72. D'Amico, J., *The F-scan system with EDG module for gait analysis in the pediatric patient.* J Am Pod Med Assoc, 1998. 88(4): p. 166-175.
73. Hsiao, H., Guan, J., Weatherly, M., *Accuracy and precision of two in-shoe pressure measurment systems.* Ergonomics, 2002. 45(8): p. 537-555.
74. Hughes, J., Pratt, L., Linge, K., Clark, P., Klenerman, L., *Reliability of pressure measurements: the EMED F system.* Cllin Biomechanics, 1991. 6: p. 14-18.
75. Young, C.R., *The F-scan system of foot pressure analysis.* Clin Pod Med Surg, 1993. 10(3): p. 455-461.
76. Podoloff, R.M., Benjamin, M.H., *A pressure mapping system for gait analysis.* Sensors, 1991: p. 21-25.
77. Anonymous, *The tekscan system.* 1998, Tekscan Inc.: Boston. p. 70.
78. Sarnow, M., Veves, A., Giurini, J.M., Rosenblum, B.L., Chrzan, J.S., Habershaw, G.M., *In-shoe foot pressure measurements in diabetic patients with at-risk feet and in healthy subjects.* Diabetes Care, 1994. 17(9): p. 1002-1006.
79. Ashruf, C.M.A., *Thin flexible sensors.* Sensor Review, 2002. 22(4): p. 322-327.
80. Kernozek, T.W., LaMott, E.E., Dancisak, M.J., *Reliability of an in-shoe pressure measurement system during treadmill walking.* Foot and Ankle Intl, 1996. 17(4): p. 204-209.

81. McPoil, T.G., Cornwall, M.W., Yamanda, W., *A comparison of two in-shoe plantar pressure measurement systems.* Lower Extremity, 1995. 2(2): p. 95-103.
82. Luo, Z.P., Berglund, L.J., An, K.N., *Validation of F-Scan pressure sensor system: a technical note.* J. Biomechanics, 1998. 35: p. 186-91.
83. Woodburn, J., Helliwell, P.S., *Observation on the F-Scan in-shoe pressure measuring system.* Clinical Biomechanics, 1996. 11: p. 301-304.
84. Xia, B., Garbaloosa, J.C., Cavanaugh, P.R. *Error analysis of two systems to measure in-shoe pressure.* in *Proceedings of the American Society of Biomechanics.* 1994.
85. Carter, J.E., Galuppo, L.D., Snyder, J.R., Willitis, N.H., *Evaluation of an in-shoe pressure measurement system in horses.* Am J Vet Res, 2001. 62(1): p. 23-27.
86. Frisbie, D.D., *Microfracture III Project Proposal.* 1998, Colorado State University: Fort Collins, CO.
87. Frisbie, D.D., *Interieukin-1 receptor antagonist delivery through adenoviral mediated gene transfer as a treatment for equine joint disease*, in *Clinical Sciences.* 1999, Colorado State University: Fort Collins, CO.
88. Bristol, R.E., Fitzpatrick, D.C., Brown, T.D., Callaghan, J.J., *Nonuniformity of contact stress on polyethylene as a bearing surface.* Clinical Biomechanics, 1996. 11: p. 75-80.
89. Sziveck, J.A., Anderson, L., Benjamin, B., *Averge and peak contact stress distribution evaluation of total knee arthroplasty.* J Arthoplasty, 1996. 11: p. 952-963.
90. Harris, M.L., Morberg, P., Bruce, W.J.M., Walsh, W.R., *An improved method for measuring tibiofemoral contact areas in total knee arthroplasty: a comparison of K-scan sensor and fuji film.* J of biomechanics, 1999. 32: p. 951-958.
91. Liau, J., Chang, C., Huang, C., Lo, W., *Effects of fuji pressure sensitive film on actual contact characteristics of artificial tibiofemoral joint.* Clinical Biomechanics, 2002. 17: p. 698-704.
92. Liggins, A.B., Hardie, W.R., Finlay, J.B., *Sterilization of Fuji pressure-sensitive film.* Med. Eng. Phys., 1994. 16: p. 496-500.
93. Clark, A.L., Herzog, W., Leonard, T.R., *Contact area and pressure distribution in the feline patellofemoral joint under hysiologically meaningful loading conditions.* Journal of biomechanics, 2002. 35: p. 53-60.
94. Bontrager, E.L., *Instrumented gait analysis systems.* 2001: p. 1-19.
95. Bland, J.M., Altman, D.G., *Statistical Methods for assessing agreement between two methods of clinical measurement.* The Lancet, 1986: p. 307-310.
96. Liggins, A.B., Finlay, J.B., *Recording contact areas and pressure in joint interfaces.*, in *Little EG*, E.M.T.T.b.H.T.E.a. Biomechanics, Editor. 1992, Elsevier Science Publishers: Amsterdam. p. 71-88.

97. Brown, T.D., Pope, D.F., Hale, J.E., Buckwater, J.A., Brand, R.A., *Effects of osteochondral defect size on cartilage contact stress.* J Orthop Res, 1991. 9: p. 559 - 567.
98. Collier, J.P., McNamara, J.L., Surprenant, V.A., Jensen, R.E., Surprenant, H.P., *All-polyethylene patellar componenets are not the answer.* Clin Orthop, 1991. 273: p. 198-203.
99. Collier, J.P., Mayor, M.B., Mcnamara, J.L., Surprenant, V.A., Jensen, R.E., *Analysis of the failure of 122 polyethylene inserts from uncemented tibial knee components.* Clin Orthop, 1991. 273: p. 232-242.
100. Fukubayashi, T., Kurosawa, H., *The contact area and presure distribution pattern of the knee: A study of normal or osteoarthritic knees.* Acta Orthop Scand, 1980. 51: p. 871-879.
101. Haut, R.C., *Contact Pressures in the patellofemoral joint during impact loading on the human flexed knee.* J Orthop Res, 1989. 7: p. 272-280.
102. Hehne, H.J., Ficker, E. Jantz, W., Mahr, D., Schopf, H.J., *A new method for measuremnts of pressure distributions and contact areas in joints.* Morphol Med, 1981. 1: p. 95-106.
103. Minns, R.J., *Wear and contact stress studies of the Minns meniscal knee prosthesis.* Eng Med, 1988. 17: p. 135-138.
104. Werner, F.W., Murphy, D.J., Palmer, A.K., *Pressures in the distal radioulnar joint: effect of surgical procedures for Kienbock's disease.* J Orthop Res, 1989. 7: p. 445-450.