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# Validation of a Three Dimensional Motion Capture System for Use in Identifying Characteristics of the Running Walk

Paul Roberson
*University of Tennessee - Knoxville*

To the Graduate Council:

I am submitting herewith a thesis written by Paul Roberson entitled "Validation of a Three Dimensional Motion Capture System for Use in Identifying Characteristics of the Running Walk." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Animal Science.

Cheryl Kojima, Major Professor

We have read this thesis and recommend its acceptance:

Henry S. Adair III, Judy Grizzle, Song-ning Zhang

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Accepted for the Council:
Linda Painter
Interim Dean of Graduate Studies

(Original signatures are on file with official student records.)

# Validation of a Three Dimensional Motion Capture System for Use in Identifying Characteristics of the Running Walk

A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Paul Roberson
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## Abstract

Validation of a Three Dimensional Motion Capture System for Use in Identifying Characteristics of the Running Walk

A three-dimensional (3-D) motion capture system was adapted for use in characterizing the biomechanics of the Running Walk, a stepping gait of the Tennessee Walking Horse (TWH) breed. Registered TWH (n = 4) were ridden through an arrangement of high-speed digital cameras at the walk (W) and running walk (RW). Infrared reflective markers (65 per horse) were used to track body segments and joint centers. Five trials per gait per horse were recorded. A dynamic 3-D model was created and used to label and track body segments. Temporal stride characteristics and joint angle values were extracted by a custom script file and gait formulas were calculated for each gait per horse. Temporal stride characteristics and gait formulas of both W and RW were found to be similar to those previously reported. Overstride (OS), which has not previously been described, increased from W to RW ($P < 0.0001$). The increase in OS accounted for 96% of the increase in stride length; only 4% of the increase in stride length is due to an increase in step length. OS was positively correlated to velocity and stride length ($P < 0.0001$), and negatively correlated to front stance duration, hind stance duration and total stance duration ($P < 0.0001$). A long OS would appear to be related to the flexibility of the proximal hind limb, the pelvis and possibly the lumbar spine. Hind stance duration as a percent of total stride time, advance placement as a percent of total stride time, and advance liftoff as a percent of total stride time did not differ between W and RW ($P > 0.05$), suggesting that the RW is not simply a faster version of W. 3-D analysis allowed for thorough analysis of joint angles. The joint angles of the carpus were highly correlated to stride length, OS, and advance placement ($P < 0.0001$), but were not correlated to velocity ($P > 0.05$). These joint angles and gait events can be viewed as velocity-independent stride characteristics and may be suitable for making comparisons between horses traveling at different velocities. Identification of joint-specific velocity-independent stride characteristics may enhance our ability to associate lameness with an individual joint.

KEYWORDS

horse

gait

biomechanics

# Preface

The terms “variables” and “characteristics” are used interchangeably, and refer to the different components of the equine stride. All figures and tables referred to in the text are located in the Appendix.

# Table of Contents

# List of Tables

## List of Figures

# I. A Review of Literature

## *A. Early Studies of Equine Locomotion*

In 1887 Muybridge made the first series of photographic records of equine locomotion[1]. Since then more than 1000 gait formulas have been identified in quadrupeds; 167 of these have been associated with equine movement and 55 are unique to equines performing symmetrical gaits (Hildebrand 1965). Gait formulas are comprised of hind stance duration as a percent of total stride time and advance placement time as a percent of total stride time (Hildebrand 1965). The first number of the formula is hind stance as a percent of stride duration, and the second number of the formula is the lag time of the front hoof in relation to the hind hoof as a percent of total stride time. A large number in the first position compared to a smaller number in the first position of the gait formula is an indication of a slower velocity; so a horse with a gait formula of **6**6-33 has a slower velocity than a horse with a gait formula of **4**6-33. The second number in a gait formula of 66-**33** indicates the hind hoof is 33% of the stride duration ahead the front hoof.

Other components of equine locomotion that have been studied are velocity of the gait and front stance duration as a percent of hind stance duration. The velocity at the walk for Quarter Horses (1.39 and 1.57 m/s) is different than the velocity for Belgians at the walk (0.81 m/s; Hildebrand, 1965). Front stance duration as a percent of hind stance duration ranged from 95% to 104% (Hildebrand 1965).

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[1] All definitions are located in the Appendix.

Terminology used to describe equine gaits has been varied and confusing and has developed with little if any scientific foundation (Leach and Crawford 1983). These and other issues concerning equine locomotion were expounded upon resulting in the generation of 15 focus areas designed for the systematic development of understanding of the locomotion of Thoroughbreds (Figure A-1) and the generation of 11 focus areas for Standardbreds (Leach and Crawford 1983). The first priority was to standardize the terminology used to describe components of a stride. Terminology used to identify the components of the walk, trot and gallop was developed, it was also recommended that certain information concerning the general characteristics of the variables of locomotion being studied be included in research papers to permit adequate comparisons between studies (Leach *et al.* 1984).

Research into Two-Dimensional (2-D) equine locomotion became focused on some of these recommendations. As research into the uniqueness of equine locomotion progressed, one concept became an important component of equine gait analysis: observation of as few as three strides from an individual horse is sufficient to develop an accurate representation of how that horse will move (Drevemo *et al.* 1980b; Hildebrand 1965; Leleu *et al.* 2004).

Two-Dimensional (2-D) kinematic components of the trot and pace (the two symmetrical racing gaits of the Standardbred) were among the first of the symmetrical gaits to be described in detail (Drevemo *et al.* 1980a; Drevemo *et al.* 1980b; Drevemo *et al.* 1980c; Fredricson *et al.* 1972; Wilson *et al.* 1988a; Wilson *et al.* 1988b). High speed 16mm film cameras tracked paper dots affixed to the skin of the horse and permitted the tracking of movement of multiple body segments simultaneously. In trotting horses pulling a cart around a racetrack, the swing and stance phase portions of the stride were found to differ significantly between all limbs and the swing portion of the stride was found to account for 75% of the total stride duration (Drevemo *et al.* 1980b). The pace was evaluated under racing conditions; estimated body segment joint centers were tracked using high speed movie cameras. The film was then digitized for evaluation. These racing horses were grouped into high and low position finishers to identify differences in temporal values between winning and losing horses. It was found that horses finishing in high positions had a greater range of motion of the fore and hind limbs than horses finishing in low positions; and horses finishing in high positions maintained or increased velocity throughout a race (Wilson *et al.* 1988a; Wilson *et al.* 1988b).

### *B. Breed Differences*

Gait evaluations of other breeds of horses found differences in stride characteristics related to level of performance, breed, conformation and age. Significant differences were found in the gait characteristics of Swedish Warmbloods judged as good or poor performers of the trot (Holmstrom *et al.* 1994). Good performers had longer stride durations and shorter fore and hind stance durations. Breed specific differences in gait characteristics and conformation of Andalusions, Arabians and Anglo-Arabians performing the trot (a gait common to all three breeds) indicated that breed differences complicated assigning specific kinematic properties to a gait performed by more than one breed (Cano *et al.* 2001). In galloping thoroughbreds, significant differences in velocities related to the change in the angle of the fetlock joint were associated with increasing age; and indicated that there may be development changes associated with differences in some joint characteristics (Butcher *et al.* 2002).

A limited amount of work has been done describing the kinematics of horses that perform the stepping gaits. Stepping gaits are four beat gaits and can be either lateral or diagonal; one hoof is always in contact with the ground. The timing of hoof placement is described as having diagonal or lateral couplets (Nicodemus and Clayton 2003). The timing of hoof placement has been used to describe the stepping gaits.

Stance duration, advance lift off, advance placement and several other temporal characteristics of the TWH running walk (RW) have been described based on 2-D data (Nicodemus and Clayton 2003). The velocity at which the RW is performed has been shown to have a significant effect on kinematic variables of the gait (Nicodemus *et al.* 2002). In a human kinematics study runners ran at three velocities and three timing patterns. The results indicated that not all temporal stride characteristics are velocity dependent. The ankle, knee and hip joint angle rates of change were more affected by changes in velocity than was angular displacement of those joints (Karamanidis *et al.* 2003).

### *C. New Technologies for Gait Assessment*

With advances in technology have come new ways to view and evaluate equine locomotion. The equine treadmill has allowed collection of large amounts of data. Through the use of the treadmill, data from multiple strides is collected while the horse and the equipment remain relatively stationary. This significantly reduces the area needed for data collection. Through the use of the treadmill, Peham *et al*. (1998) demonstrated that horses may have a preferred speed of locomotion and that a horse moving at a non-preferred speed will be inconsistent in the motion pattern of its hooves. There are disadvantages to the treadmill; horses running on a treadmill move with an un-natural gait pattern compared to horses running on a track. Horses running on a treadmill do not normally carry a rider or pull a cart. And finally, horses running on treadmills require a long period of adaptation prior to the start of data collection (Oldruitenborgh *et al.* 1999).

A metal plate with force sensors that is mounted in the path of travel of a horse or human can be used to detect the point at which heel contact is made. This point identifies the beginning of the stance phase of a stride. The force plate generates three dimensional information regarding the ground reaction force (GRF) being applied to the foot during the stance phase. Another accurate indicator of the stance phase without the use of a force plate is foot velocity. During a stride the velocity that occurs most often in the hoof is associated with stance time (Peham *et al.* 1999).

Tracking markers applied to the horse’s body allowed researchers to track anatomic segments of the horse. The incorporation of tracking markers affixed directly to the skin of the horse creates large errors in the data, especially if the markers are affixed over bony prominences such as those markers placed in joint areas. The error occurs as a result of soft tissue artifact  movement under the marker (Fredricson *et al.* 1972). Soft tissue artifact (STA) has been identified by researchers of human biomechanics as the greatest contributor to error (Cappello *et al.* 1997; Cappozzo *et al.* 1997). In humans, markers attached to body segments or joint centers proximal to the ankle joint generate greater error from skin movement than do distal body segments or joint centers (Andriacchi and Alexander 2000); this was also found to be true in horses (van Weeren *et al.* 1990). Surgically implanted LEDs were used for quantification of STA in horses and found that error was greatest along the body segment axis and that error in tracking the greater trochantor with a single marker may be more of a result of the lack of the movement of the skin in relation to the movement of the underlying joint center (van Weeren *et al.* 1990).

### *D. Improving Accuracy*

Researchers have developed methods to overcome some of the problems associated with STA. A tracking marker cluster attached to the skin of a single body segment, point cluster technique (PCT), was found to generate less error than a single marker attached to the skin of a body segment provided the location of each marker was not in an area of high STA (Cappozzo *et al.* 1997; Sha *et al.* 2004). Using rigid form marker clusters further reduces artifact movement error when used with markers that identify the underlying anatomical landmarks that are being tracked (Cappozzo *et al.* 1995). A minimum of three markers per cluster are required to take advantage of the redundancy created by marker clusters (Cappozzo *et al.* 1997; Cheze *et al.* 1995).

Tracking anatomic landmarks with three dimensional (3-D) markers as apposed to planer markers further reduces error propagation during movement analysis (Cappello *et al.* 1996). When a static image is created from the subject that has tracking marker clusters and anatomical markers attached, the static image can be used as a reference template for body segments to further decrease error from STA. The calibrated anatomical systems technique (CAST) uses both a static and dynamic data set for movement analysis. This allows anatomical markers to be removed during the data collection period, and still permits 3-D tracking of a segment during rotational and translational movement (Cappozzo *et al.* 1995).

### *E. Rationale*

The Tennessee Walking Horse performs the running walk, a stepping gait unique to the breed. It has been suggested that the running walk is the walking gait performed at a faster velocity (Nicodemus *et al.* 2002). Breed differences that have been studied demonstrate the need to evaluate each breed individually, and that inferences about specific gait characteristics cannot be made across breeds (Cano *et al.* 2001).

Developing clinically relevant data requires that the horse be studied under conditions as close as possible to the conditions in which it is normally used, with as few restrictions on movement as possible. When gait performance of the Tennessee Walking Horse is being studied, saddled horses ridden without encumbrances in an arena should provide the most accurate data compared to similar studies performed using treadmills, 2-D analysis.

It is expected that by adapting the currently accepted methodology (PCT and CAST) of human biomechanics, that a complete 3-Dimensional model of equine movement can be generated, and that error associated with planar markers and 2-D studies can be reduced. Additionally, development of this model may lead to the generation of clinically relevant data for lameness evaluation or the detection of sub-clinical gait abnormalities.

The following study describes the first time that PCT and CAST have been used for 3-Dimensional equine gait analysis of a horse under saddle in an open arena.

### *F. Hypothesis*

The hypothesis of this research is that there are differences in the locomotion patterns between the walk and the running walk of the TWH identifiable through the adaptation of PCT and CAST for use in three-dimensional analysis.

# II. Chapter I

# Adaptation of the Point Cluster and Calibrated Anatomical System Techniques for Use in Evaluating the Kinematics of the Tennessee Walking Horse

## *I. Introduction*

### A. Use of Coordinate Systems

Describing the 3-Dimensional position of an rigid body relative to the laboratory can be accomplished by relating the position and angles of the rigid body's local coordinate system (LCS) to the global coordinate system (GCS) using (X, Y, Z; Figure A-2)  (Cappello *et al.* 1997). Relating the two coordinate systems to each other creates 6 degrees of freedom (DOF) within the object. Describing the 2-D position of a rigid body permits 3 DOF (X, Y). Two-Dimensional motion analysis does not fully describe a rigid body in motion. A right handed GCS used for 3-D analysis can be described as follows. The X axis is medial/lateral in direction and is the pivot point of flexion and extension. Movement to the left of the origin is positive to the right is negative. The Z axis runs vertically and is the pivot point of adduction and abduction. Upward movement from the point of the origin is in the positive direction. The Y axis is in the anterior/posterior direction and is the pivot point of inversion and eversion. Forward movement from the point of origin is in the positive direction.

A limited amount of work has been done describing the kinematics of horses that perform the stepping gaits. The TWH performs a stepping gait that is unique to the breed, the running walk. Stance duration, advance lift off, advance placement and several other temporal characteristics of the TWH running walk have been described based on 2-D data (Nicodemus and Clayton 2003). The velocity at which the RW is performed has been shown to have a significant effect on some characteristics of the gait, such as stance duration and stride length. (Nicodemus *et al.* 2002). In a human kinematics study it was shown that changes in velocity do not create variability in all stride characteristics; variability was related to additional parameters currently under investigation (Karamanidis *et al.* 2003). For instance, the angles of the ankle, knee and hip joints at heel strike and toe off were similar across three velocities and three stride frequencies.

Few studies have focused on the 3-Dimensional (3-D) kinematics of the horse. Two separate studies used Steinmann pins (pins surgically implanted into the bone) and 25 mm reflective markers to establish 3-D coordinates, and observe the 3-D kinematics of the carpal and tarsal joints in hand led trotting horses (Clayton *et al.* 2004; Lanovaz *et al.* 2002). This technique is highly invasive and does not allow for the natural movement of the subject (Andriacchi and Alexander 2000).

## B. Non-invasive Techniques

A less invasive technique is available in which markers are directly applied to the skin of the horse. However, this technique is associated with large errors in the data, especially if the markers are affixed over bony prominences such as joint areas. The error occurs as a result of soft tissue artifact (STA) under the marker (Fredricson *et al.* 1972). STA has been identified by researchers of human biomechanics as the greatest contributor to error. In humans the more proximal a body segment or joint center is to the ankle joint, the greater the error created by skin movement (Andriacchi and Alexander 2000). This was also found to be true in horses (van Weeren *et al.* 1990).

The point cluster technique (PCT) was developed to reduce STA. PCT uses marker clusters to establish the coordinate system and track anatomic landmarks. When a 3-D marker cluster with 3 or more non-planer markers is attached to the skin of a single body segment in an area of low STA, the error associated with STA is lowest (Cappozzo *et al.* 1997; Cappozzo *et al.* 1995; Cappozzo *et al.* 1996; Cheze *et al.* 1995; Sha *et al.* 2004).

The use of a control is common to all areas of science. The control for a kinematic study can be a static image of the subject with all relevant markers attached. The static image is used as a reference template of the body segments. When the associations between the static image and the dynamic images of the motion trials are created, the amount of error from STA is reduced. The calibrated anatomical systems technique (CAST) uses both a static and dynamic data set for movement analysis. CAST allows anatomical markers to be removed during the data collection period and still permits 3-D tracking of body segments (Cappozzo *et al.* 1995).

## C. Rationale

The use of  PCT and CAST allow for 3-D tracking of joint centers and body segments without the use of invasive procedures and reduces the amount of error associated with STA (Buczek *et al.* 1994; Cappello *et al.* 1997; Cappozzo *et al.* 1997; Cappozzo *et al.* 1995). 3-D analysis gives a more complete picture of locomotion than does 2-D analysis. Use of the techniques requires that several assumptions are made: (1) that the tracking markers are on a rigid form and that the form is placed in an area of low STA on the segment, (2) that there is no distortion of the form, and (3) that if the markers identifying joint centers are placed on each subject by the same person then the variation between the estimated and true joint centers will be similar (Coutts 1999).

Studies of normal and abnormal human locomotion have demonstrated that a greater understanding of kinematics has a direct clinical benefit by increasing the ability of practitioners to identify or classify sub-clinical abnormalities in locomotion (Andriacchi and Alexander 2000; Coutts 1999). Currently available 3-D gait analysis technologies that are used in human gait analysis studies can be adapted to the horse. In the experiment described below the current technologies have been adapted specifically to describe the 3-D kinematics of the running walk performed by the Tennessee Walking Horse under normal riding conditions. This can be accomplished through the use of the non-invasive PCT and CAST. These techniques can also be used to generate a 3-D model for the visual assessment of the gait and may lead to the development of a clinically relevant model for use in identifying sub-clinical lameness in horses.

## *II. Materials and Methods*

### A. Laboratory Environment

Four horses were ridden through an arrangement of a six camera motion analysis system (120 Hz, VICON, Oxford, UK) at the walk (condition 1) and at the running walk (condition 2). Fourteen body segments were marked and tracked for data collection. There were four joints and six body segments of the left side of the horse that were the primary focus in this study (Table A-1). A 15 foot wide track composed of sandy loam soil spread a minimum of four inches deep was constructed in an 80’ x 160’ indoor arena with a concrete floor. All cameras were elevated approximately three to five meters above the track surface. The tripod-mounted cameras were equipped with infra-red strobes and were arranged to create a data capture volume 6m length x 4m wide x 3m high, approximately 72 cubic meters. A VICON 460 data station controlled by a desktop computer was used to operate the 6 cameras. Four cameras were placed on the inside of the track and two cameras were placed on the outside of the track (Figure A-3). Prior to building the track, a 3” polyvinyl chloride pipe was positioned near the data collection station to allow the power and data cables operating the two outside cameras to be run under the track. Two removable reflective markers were affixed to the permanent barrier on the outside of the track and were placed 6 meters apart parallel to the horses’ path of travel (Figure A-3). The removable markers were aligned with two digital timers used to calculate the velocity of each horse during dynamic data collection sessions.

## B. Markers

A total of 65 markers were used to identify or track the movement of body segments and joint centers during the data collection process. Text files were created to establish a labeling convention for the markers. The text files were then incorporated into the VICON software program for use in labeling and identifying each marker in the raw data collection trials. Labeling the markers generated the association between the markers and the bone-embedded frame of each segment (Table A-2). The dynamic marker set was used during data collection; anatomical markers were removed from the static marker set to create the dynamic marker set. The naming convention of the markers was developed to make each marker readily and individually identifiable.

Markers were constructed of acrylic spheres14mm in diameter threaded onto a plastic base and covered with 3M® infrared reflective tape. Rigid thermoplastic forms were constructed to hold a marker cluster of two, three or four markers. The PCT takes advantage of the redundancy created when more than one marker is used to describe the position of a body segment (Cappozzo *et al.* 1997). Markers that were parts of a cluster were arranged in a non-collinear pattern, with the greatest distance between makers associated with the long axis of a segment. Marker clusters were assembled with adequate space between markers and followed recommended guidelines for biomechanical studies (Cappozzo *et al.* 1997). The thermoplastic forms were then affixed to the horse by the use of a self adhesive tape wrapped around a body segment or by use of a hook and loop fastening system with double-sided tape; individual markers were also affixed to the horse. Marker arrays attached to the horse were tracking markers and were on the horse during all data collection performed on that horse. Individual markers were considered to be anatomical or tracking markers based on their location. In the instance of the metacarpophalangeal joint a single marker served as both an anatomical and tracking marker.

## C. Calibration and Data Collection

Prior to camera calibration, the two reflectors used for the timers were removed so they would not interfere with the procedure.  Static and dynamic camera calibrations were performed at the beginning of each data collection session. Static camera calibration was performed by a proprietary program, Dynacal, in the VICON system. Through the use of an L-frame of a known size with reflective markers attached, the Dynacal program established the 3-D lab coordinate system and origin. The L-frame was placed in the approximate center of the data collection area. The Dynacal program oriented the cameras to each other and the L-frame establishing the volume area that the cameras viewed during the dynamic calibration as well as the origin of the GCS (Figure A-4). Dynamic calibration was accomplished by moving a T-wand, fitted with reflective markers on the crossbar, throughout the collection volume as randomly as possible. Ideally, random error from dynamic calibration should be less than 2%. The error was checked immediately after the dynamic calibration process. If the error level exceeded 2% the process was repeated as necessary until error was within acceptable limits.

Anatomical markers were attached to the medial and lateral sides of selected joint centers (Table A-1) to define the anatomical frame (Cappozzo *et al.* 1995). The joint centers were used to define the proximal and distal ends of a joint segment. Individual tracking markers were attached to the horse in the same manner as the anatomic markers. Tracking markers and anatomical markers were used to establish a static data collection file for each horse (Figure A-4). An acceptable static trial was determined to be one in which all tracking markers were visible and at least one anatomical marker for each joint center was visible. Anatomical markers were then removed for dynamic data collection. Each horse was ridden at the walk (condition 1) and the running walk (condition 2); the order of conditions was randomly assigned. The horse was ridden through the collection area until five good trials for a single condition had been collected. The time in seconds it took each horse to move through the collection area was recorded from the digital timer. The horse was then ridden through the collection area under the alternate condition. Again, five trials and the time were collected for that condition. Markers were removed after five trials for each of the two conditions were collected.

### D. Data Reconstruction and Labeling

Key components of data reconstruction, which are adjusted by the user, include the Intersection Limit and the Predictor Radius. The Intersection Limit is the maximum allowable distance between two camera rays tracking a single marker. If the rays of multiple cameras fix the marker position of an individual marker outside this maximum, then that marker may not be visible so low values may eliminate markers. If all markers from the marker set are present then the Intersecting Limit is adequate. The Predictor Radius uses data of the next frame to determine the likelihood that the data is a continuation of the current frames trajectory. If the Predictor Radius value is set too high then trajectories may reverse position; if it is set too low then there may be breaks in trajectories that are in fact the same trajectory. Failure to detect the optimal Predictor Radius results in an increase in trajectory labeling time or may require the trajectories to be manually labeled but should not adversely affect the results unless marker reversal goes undetected. Marker flipping is relatively obvious and can be detected by color highlighting the suspect markers to see if their locations change abnormally. If the proximal marker suddenly becomes the distal marker the trajectories are identified and can easily be corrected. Correction can be accomplished by resetting the reconstruction parameters or by editing the marker trajectories directly. The optimal reconstruction parameters are subjective, but it can be assumed that if all markers are present and there is no marker flipping or marker distortion then acceptable reconstruction parameters are being used.

For each horse, acceptable data reconstruction parameters were determined by subjective visual inspection of the trajectories of each marker, and then applied to all data obtained from the horse. Data from the static and dynamic trials were reconstructed using the same parameters. The optimal reconstruction parameters may have varied between subjects. For each horse, the static trial that best met the established criteria was labeled by associating the static trial with the static marker set. Motion trials were edited to begin one to two frames before the first frame of data and end one to two frames after the last frame of data.

## E. Building of a Three-Dimensional Model

Visual3D software (C-motion Inc., Rockville, Maryland) was used to create a dynamic 3-D bone model from the collected motion trials.  A static trial from a horse was imported into Visual3D. The Model Building module was used to label and associate static and dynamic marker labels with the body segments that were tracked during data collection. Virtual markers called “Landmarks” were generated manually to aid in the identification of joint centers and complete the labeling of the 3-D model. Raw data from the motion trials were imported and associated with the labeled model. Through the use of Pipeline, an interactive script generator module, data interpolation and a low pass filter at 4 Hz was applied to the data in the motion trials.  The interpolation was used to fill gaps in the data of 10 frames or less and the low pass filter was used to smooth the data.

The Signal and Event Processing module allowed the data from different segments to be associated so that joint angles could be calculated. The data was linked by defining the proximal and distal segments of each joint. The proximal segment was the reference segment. For the carpal joint, the radius was the reference segment and the third metacarpal was the segment of interest. The carpal joint angle was calculated as the angle of the third metacarpal with regard to the radius. The linking process was completed for the other joints being tracked. Once the data was linked, graphs were generated to observe the changes in the joint angles as the horse moved.

Four specific gait events were used to calculate the temporal stride characteristics of the walk and running walk: left hind hoof heel strike (LHHS); left front hoof heel strike (LFHS); left hind hoof toe off (LHTO); left front hoof toe off (LFTO) (Table A-3). At the point of each gait event the relative angles of the LCS of the carpal joint and the LCS of the metacarpophanangeal joint were determined for later comparison of the walk and running walk. Stride length was calculated as the distance between two successive LFHS or two successive LHHS. Advance placement is the time difference from the LHHS to the LFHS. Advance lift off is the time from LHTO to LFTO. Stance duration is the time from heel strike to toe off of an individual hoof. Stride duration is the time value of stride length. Overstride is a unique component of the TWH running walk. Overstride was calculated as the distance between the LFHS of one stride and the LHHS of the subsequent stride.

The point at which heel strike occurred was determined by visual observation of the moving 3-D model, hoof velocity in the z axis graph and the carpal and tarsal joint angle graphs. Heel strike occurred when hoof velocity along the z axis was minimal. The point at which toe off occurred was determined by visual observation of the moving 3-D model, hoof velocity in the y axis graph and the carpal and tarsal joint angle graphs. Toe off occurred when hoof velocity along the y axis changed from increasing at an increasing rate to increasing at a decreasing rate (see figure A-5).

The marker associated with the coronary band was the primary marker used to determine stride length. If the coronary band marker was not visible at the beginning and end of a stride then the heel marker for that stride was used to determine the stride length. The length of overstride was determined in the same manner as stride length. All temporal stride characteristics and joint angle values were extracted from the motion trials by developing a custom script file for use in the Pipeline Processing module in Visual3D, for script (see http://web.utk.edu/~proberso/).

Gait formulas are comprised of hind stance duration as a percent of total stride time and advance placement as a percent of total stride time. The first number of the formula is hind stance as a percent of stride duration. The second number of the formula is the amount of time between hind hoof heel strike and front hoof heel strike on the same side as a percent of total stride time. A large number in the first position compared to a smaller number in the first position of the gait formula is an indication of a slower velocity. So a horse with a gait formula of **66**-33 has a slower velocity than a horse with a gait formula of **46**-33. The second number in a gait formula of 66-**33** indicates the hind hoof is 33% of the stride duration ahead the front hoof. If a stride takes 1 second to complete, hind hoof heel strike occurs at time zero, front hoof heel strike occurs at time 333 m/sec and hind hoof heel strike occurs again at 1 second.

## F. Statistical Analysis

Statistical analysis of stride characteristics was performed using the analysis of variance model in SAS 9.1.3 (SAS, 2002). A Randomized Block Design with replication was used. Each block was a horse and each block received two treatments (walk and running walk) with five replications of each treatment collected.

Only correlations produced from 18 or more trials were considered to be valid. A correlation with 18 trials indicated that data was from three horses, three trials each under two conditions. Correlations of temporal stride characteristics and joint angle values at specific gait events were determined. Since only the left side of each horse was tracked no diagonal stride characteristic comparisons were made.

## *III. Results*

Data was available from four horses at the walk and three at the running walk. The running walk data for the fourth horse was not used because there was no advance lift off or advance placement in the stride. This indicated that the horse was performing a pace not the running walk. Descriptive statistics were generated for the body segments that were tracked (Table A-4). There was little difference in the body structure of the horses from which motion data was collected.

Tables 5 and 6 contain the descriptive statistics for the stride characteristics of the walk and running walk as performed by TWH. Velocity for the walk was 1.77 ± 0.127 (μ ± sem) m/s and is more similar to the reported velocity at the walk for Quarter Horses (1.39 and 1.57 m/s) than to the velocity for Belgians at the walk (0.81 m/s; Hildebrand, 1965). At the walk, front stance duration as a percent of hind stance duration was 102 %; this is in agreement with previously reported values for the front stance hind stance relationship

(Hildebrand 1965). Mean velocity of the running walk was 3.41 ± 0.138 m/s and generated the gait formula 57-22. All other temporal stride characteristics of the running walk except overstride, which has not previously been described in the walk or running walk, were found to be within the ranges associated with the temporal characteristics of the running walk (Nicodemus and Clayton 2003; Nicodemus *et al.* 2002).

A comparison between the mean temporal stride characteristics of the walk and running walk revealed that hind stance duration as a percent of total stride time, advance placement as a percent of stride time and advance lift off as a percent of stride time were not significantly different between the two gaits (Table A-7). Stride length at the walk (1.78 ± 0.061 m) increased 0.36 m to 2.15 ± 0.066 m at the running walk, a 20% increase. Overstride at the walk 0.336 ± 0.36 m increased 0.343 m to 0.679 ± 0.035 m at the running walk, 102%. Stance duration of the front and hind limbs decreased by 61%, and stride duration decreased by 44%. Velocity from the walk to the running walk increased from 1.77 ± 0.177 m/s to 3.40 ± 0.196 m/s, 93%

Correlations (Pearson correlation coefficient >0.70 and $P < 0.0001$) were found to exist between more than 40 temporal characteristics of the walk and running walk (Table A-8), and between the joint angle of the carpus at several gait events and stride length, overstride, and advance placement (Table A-9).

Overstride was found to have a positive correlation to gait, velocity and stride length ($r = 0.72$, 0.71 and 0.87 respectively; $P < 0.0001$). There was a strong negative correlation between overstride and front stance duration, hind stance duration and total stance duration (r= -0.71, -0.73 and -0.74 respectively; P < 0.0001).

In general, x axis angles were correlated to each other at each stride event (Table A-9). Similar correlations were found among the y axis angles and z axis angles at each stride event. Correlations in all three axes x, y, and z, were found to exist between the carpal joint angle at front hoof heel strike and carpal joint angle at hind toe off. The angles of the carpal joint at LHHS, LFHS, LHTO, and LFTO were correlated to each other in at least one axis. Negative correlations exist between the angles of the carpal joint at LFHS, LHTO and at LFTO and stride length and overstride (Table A-9). Similar correlations were found to exist in the metacarpophalangeal joint as well.

Velocity was negatively correlated to advance lift off and advance placement. Because of the low number of useable observations, correlations pertaining to the hind limbs were not reported. The carpal and metacarpophalangeal angles at each gait event were weakly correlated to velocity (r > 0.30, P > 0.05).

The comparison of the LCS angles of the left carpal joint at each gait event during the walk and running walk indicated that five of the 12 angles were significantly different (Table 10). The means (degrees) ± sem of the significantly different angles were: hind heel strike about the z axis (-2.6 ± 3.4: 4.0 ± 3.4), front heel strike about the x axis (-10.5 ± 1.4: -18.6 ± 1.7), front heel strike about the z axis (-4.6 ± 2.2: 0.1 ± 2.2), hind toe off about the x axis (3.9 ± 5.8: -4.5 ± 5.6) and front toe off about the x axis (-30.7 ± 3.6: -45.6 ± 4.2) for the walk and running walk respectively P < 0.05. The comparison of the LCS angles of the left metacarpophalangeal joint at each gait event during the walk and running walk indicated that two of the 12 angles were significantly different (Table 11). The means (degrees) ± sem of the significantly different angles were: front heel strike about the y axis (11.7 ± 3.2: 4.7 ± 3.6), hind toe off about the y axis (2.1 ± 1.9: -4.9 ± 2.3) for the walk and running walk respectively P < 0.05.

## *IV. Discussion*

The results presented here are in agreement with the data from two other recent studies performed on the TWH running walk (Nicodemus and Clayton 2003; Nicodemus *et al.* 2002) and a more comprehensive study on all symmetrical equine gaits (Hildebrand 1965). Data presented here regarding hind stance duration as a percent of total stride time, advance placement as a percent of total stride time and advance lift off as a percent of total stride time are all similar in value across the studies and found to be unaffected by velocity when velocity information was available (Table A-12).

It has been suggested that the velocity at which a horse travels makes comparisons between stride characteristics from different horses difficult (Clayton *et al.* 2002; Hoyt *et al.* 2002; Nicodemus *et al.* 2002; Peham *et al.* 1998). However, this does not seem to be the case for all components of stride (Karamanidis *et al.* 2003). In a comparison of the gait formulas from this study and three others on the running walk it appears that there is little difference in the gait formulas unless velocity is almost doubled. The two gait formulas associated with the highest velocities described by Hildebrand (1965) appear to be different from the low velocity gait formula and those of the three most recent studies including this one. This may be a result of differences in methodology or available technology as well as changes in training methods or conformation of the horses.

Hind stance as a percent of stride time did not change significantly with an increase in velocity or the change of gait from the walk to the running walk. Fore stance as a percent of stride time, however, did change significantly with the increase in velocity and change in gait. This change in the front limb is related to the increase in animation of the front limbs, which is common in the TWH (Hildebrand 1965).

It has been suggested that an increase in stride length is the mechanism for increasing velocity in the running walk and that the hind limb may play a role in this (Nicodemus *et al.* 2002). In this study the increase in overstride of 0.343m accounted for 95% of the increase in stride length 0.36m; only 5% of the increase in stride length is comprised of an increase in step length. The hind limb is the primary contributor of the increase in stride length and overstride in the TWH. Step length does not change significantly between the walk and the running walk. If step length did increase then there would be a smaller increase in overstride compared to the increase in stride length. If step length shortened to generate the increase in overstride then the increase in overstride would be greater than the increase in stride length. This method of increasing stride length has not been previously identified in the TWH.

Based on these results overstride would seem to be related to the flexibility of the proximal hind limb, pelvis and possibly the lumbar spine. Overstride may be a necessary kinematic component of the running walk. In order to shorten fore limb stance duration as a percent of stride duration and generate the animated motion of the fore limbs, the hind limb reaches forward to be positioned more directly under the center of mass of the horse. This would move the center of mass toward the hind limbs reducing the mass supported by the fore limbs making it easier for the fore limbs to be elevated.

The correlations noted between the four gait events provide the opportunity to take equine gait analysis in a new direction. The carpal joint angles associated with the gait events were not correlated to velocity but correlated to each other and stride length, overstride and advance placement. These joint angles then can be viewed as velocity–independent stride characteristics and may make them suitable for comparisons of locomotion patterns between horses.

Within the LCS of the carpal joint the relative angles that differed from the walk to the running walk at the gait events are the same angles that are strongly correlated to stride length, overstride and advance placement. These results should be expected and confirm that the kinematics of the TWH running walk are different than the kinematics of the walk.

Without a 3-D model, stride characteristics cannot be fully or accurately described. The kinematics of the horse can be accurately determined through the use of PCT and CAST. Use of these non-invasive techniques has allowed for the accurate evaluation of kinematic variables of the Tennessee Walking Horse performing the walk and running walk under normal riding conditions. These results compare favorably with the results of earlier studies describing the temporal values that are associated with the running walk. Further development of these techniques on the whole horse may lead to the development of a clinically relevant method of gait evaluation.

# III. Chapter II

## Differences in the Kinematics of the Tennessee Walking Horse at the Walk and Running Walk

## *I. Introduction*

### A. Early Studies of Equine Locomotion

In 1887 Muybridge made the first series of photographic records of equine locomotion. Since then more than 1,000 gait formulas have been identified in quadrupeds, 167 of these formulas have been associated with equine movement and 55 are unique to equines performing symmetrical gaits (Hildebrand 1965). Gait formulas are comprised of hind stance duration as a percent of total stride time and either advance placement as a percent of total stride time or advance lift off as a percent of total stride time. The first number of the formula is hind stance as a percent of stride duration, and the second number of the formula is the lag time of the front hoof in relation to the hind hoof. A large number in the first position compared to a smaller number in the first position of the gait formula is an indication of a slower velocity. So a horse with a gait formula of **66**-33 has a slower velocity than a horse with a gait formula of **46**-33. The second number in a gait formula of 66-**33** indicates the hind hoof is 33% of the stride duration ahead the front hoof.

Terminology used to describe equine gaits has been varied and confusing and has developed with little if any scientific foundation (Leach and Crawford 1983). These and other issues concerning equine locomotion were expounded upon resulting in the generation of 15 focus areas designed for the systematic development of understanding of the locomotion of Thoroughbreds (Figure A-1) and the generation of 11 focus areas for Standardbreds (Leach and Crawford 1983).

The first priority was to standardize the terminology used to describe the components of the equine stride. Terminology used to identify the components of the walk, trot and gallop was developed and it was recommended that information pertaining to the characteristics of the variables being studied, should be included in research papers to permit adequate comparisons between studies (Leach *et al.* 1984). Research into 2-Dimensional (2-D) equine locomotion became focused on some of these recommendations.

As research into the uniqueness of equine locomotion progressed, one concept became an important component of equine gait analysis: observation of as few as three strides from an individual horse is sufficient to develop an accurate representation of how that horse will move (Drevemo *et al.* 1980b; Hildebrand 1965; Leleu *et al.* 2004). Gait evaluations conducted on different breeds of horses have found differences in stride characteristics related to level of performance, breed, conformation and age (Butcher *et al.* 2002; Cano *et al.* 2001; Holmstrom *et al.* 1994).

A limited amount of work has been done describing the kinematics of horses such as the TWH that perform the stepping gaits. Stance duration, advance lift off, advance placement and several other temporal characteristics of the TWH running walk (RW) have been described based on 2-D data (Nicodemus and Clayton 2003). The velocity at which the RW is performed has been shown to have a significant effect on kinematic variables of the gait (Nicodemus *et al.* 2002). In a human kinematics study it was shown that changes in velocity do not create variability in all stride characteristics; variability is related to additional parameters currently under investigation (Karamanidis *et al.* 2003). For instance, the angles of the ankle, knee and hip joints at heel strike and toe off were similar across three velocities and three stride frequencies.

### B. Use of Coordinate Systems

Describing the 3-Dimenssioanl position of an rigid body relative to the laboratory can be accomplished by relating the position and angles of the rigid body's local coordinate system (LCS) to the global coordinate system (GCS) using (X,Y, Z; Figure A-2)  (Cappello *et al.* 1997). Relating the two coordinate systems to each other creates 6 degrees of freedom (DOF) within the object. Describing the 2-D position of a rigid body permits 3 DOF (X, Y). Two-Dimensional motion analysis does not fully describe a rigid body in motion.

### C. Rationale

The walk, trot and pace are the only symmetrical gaits of horses that have been included in the literature for systematic evaluation. There are characteristics of equine locomotion, hind stance (% of total stride), lateral advance lift off (% of total stride) and lateral advance placement (% of total stride) that may be able to be used as indicators of future performance and also have clinical relevance in lameness diagnosis. The general assessment of these gait characteristics may not translate well across breeds even if the same gait is being performed. These breed differences may be related to the differences in conformations of the breeds.

Because the data obtained from horses on a treadmill does not reflect the natural motion of a horse under riding conditions, equine gait analysis should be conducted under normal use conditions. Non-invasive techniques used for human locomotion studies have been adapted for evaluating 3-D equine locomotion under normal riding conditions (Chapter 1). These techniques have led to the development of the first 3-D model of a horse being ridden under saddle during normal riding conditions. This 3-D model and the associated methodology may lead to a better understanding of equine locomotion. With increased understanding it may be possible to develop methods of equine gait evaluation by which to predict future performance.

### D. Hypothesis

The hypothesis of this research is that there are differences in the locomotion patterns between the walk and the running walk of the TWH identifiable through the adaptation of PCT and CAST for use in three-dimensional analysis

## *II. Materials and Methods*

### A. Laboratory Environment

A 15 foot wide track composed of sandy loam soil spread a minimum of four inches deep was constructed in an 80’ x 160’ indoor arena with a concrete floor. The track used one side and one end of the arena. A permanent barrier marked the outside of the track, and a temporary barrier constructed of highly visible nylon rope and wooden posts marked the inside of the track. Four registered Tennessee Walking Horses were ridden through an arrangement of a six camera motion analysis system (120 Hz, VICON, Oxford, UK) at the walk (condition 1) and at the running walk (condition 2). Electronic timers were used to calculate the velocity of the horse during each trial (Figure A-3).

### B. Markers

A total of 65 infrared reflective markers were used to identify or track the movement of body segments and joint centers during the data collection process. Markers were acrylic spheres 14mm in diameter threaded onto a plastic base and covered with 3M® infrared reflective tape. Marker clusters consisting of two to four markers were affixed to the horse by the use of a self adhesive tape wrapped around a body segment, or by use of a hook and loop fastening system with double-sided tape. Individual markers were also affixed to the horse. Marker clusters attached to the horse were tracking markers and were on the horse during all data collection performed on that horse. Anatomical markers were attached to the horse to identify the proximal and distal ends of body segments.

### C. Calibration and Data Collection

Static and dynamic camera calibration was performed at the beginning of each data collection session. A static trial was captured for each horse prior to the collection of any dynamic trials. The anatomical markers were then removed for dynamic data collection. Each horse was ridden through the data capture volume area under both conditions; the order of the conditions was randomly assigned. Each horse was ridden through the collection area until five good trials for a single condition had been collected. The time in seconds it took each horse to move through the collection area was recorded from the digital timer.

## D. Data Reconstruction and Labeling

For each horse, acceptable data reconstruction parameters were determined by subjective visual inspection of the trajectories of each marker, and then applied to all data obtained from the horse. Data from the static and dynamic trials were reconstructed using the same parameters. The optimal reconstruction parameters may have varied between subjects. For each horse, the static trial that best met the established criteria (Chapter 1) was labeled by associating the static trial with the static marker set. Motion trials were edited to begin one to two frames before the first frame of data and end one to two frames after the last frame of data. Body segment lengths were obtained from the static trial by measuring the distance between the anatomical markers at the proximal and distal ends of each body segment.

## E. Building a Three-Dimensional Model

Visual3D software (C-motion Inc., Rockville, Maryland) was used to create a dynamic 3-D bone model from the collected motion trials. A static trial was imported into Visual3D. The Model Building module was used to label and associate the static and dynamic marker labels with the body segments that were tracked during data collection.

Four specific gait events were used to calculate the temporal stride characteristics of the walk and running walk: left hind hoof heel strike (LHHS); left front hoof heel strike (LFHS); left hind hoof toe off (LHTO); left front hoof toe off

(LFTO) (Table A-4). Stride length was calculated as the distance between two successive LFHS or two successive LHHS. Advance placement was determined as the time difference from the LHHS to the LFHS. Advance lift off was determined as the time from LHTO to LFTO. Stance duration was determined as the time from heel strike to toe off of an individual hoof. Stride duration was determined as the time value of stride length. Overstride, a unique component of the TWH gaits, was calculated as the distance between the LFHS of one stride and the LHHS of the subsequent stride.

The point at which heel strike occurred was determined by visual observation of the moving 3-D model, the heel marker or the coronary band marker when the heel marker was not present, and the carpal and tarsal joint angle graphs. Heel strike occurred when hoof velocity along the y axis was minimal. Toe off occurred when hoof velocity along the y axis changed from increasing at an increasing rate to increasing at a decreasing rate (Figure A-5). Information was extracted from the motion trials through the use of the Pipeline Processing module for; temporal stride characteristics, joint's range of motion, joints angles at each gait event.

Gait formulas are comprised of hind stance duration as a percent of total stride time and either advance placement as a percent of total stride time or advance lift off as a percent of total stride time. The first number of the formula is hind stance as a percent of stride duration, and the second number of the formula is the lag time of the front hoof in relation to the hind hoof. A large number in the first position compared to a smaller number in the first position of the gait formula is an indication of a slower velocity. So a horse with a gait formula of **66**-33 has a slower velocity than a horse with a gait formula of **46**-33.

### F. Statistical Analysis

Statistical analysis of stride characteristics was performed using the analysis of variance model in SAS 9.1.3 (SAS, 2002). A Randomized Block Design with replication was used. Each block was a horse and each block received two treatments (walk and running walk) with five replications of each treatment collected. The mean and standard deviation were determined for the body segment lengths of the four horses that provided the final data.

Only correlations produced from 18 or more trials were considered to be valid. A correlation with 18 trials indicated that data was from three horses, three trials each under two conditions. Correlations of temporal stride characteristics and joint angle values at specific gait events were performed. Since only the left side of each horse was tracked no diagonal stride characteristic comparisons were made.

## *III. Results*

Useable data was available from four horses at the walk and three at the running walk. Data was obtained from four to six trials, at the walk, for each horse. Descriptive statistics were generated for the body segments that were tracked (Table A-4). There was little difference in the body structure of the horses.

In general, x axis angles were correlated to each other at each stride event. Similar correlations were found among the y axis angles and z axis angles at each stride event. Correlations of temporal stride characteristics and joint angle values at specific gait events were performed. Pearson correlation coefficients ($r > 0.700$; $P < 0.05$) make up the majority of the reported correlations (Table A-8). Since only the left side of each horse was tracked no diagonal stride characteristic comparisons were made.

Correlations in all three axes x, y, and z, were found to exist between the carpal joint angle at front hoof heel strike and carpal joint angle at hind toe off. The angles of the carpal joint at LHHS, LFHS, LHTO, and LFTO were correlated to each other in at least one axis. Negative correlations were shown between the angles of the carpal joint at LFHS, LHTO and at LFTO and stride length and overstride (Table A-9). Similar correlations were found in the metacarpophalangeal joint.

Of the 20 trials performed at the walk, velocity data was obtained from 19 trials; hind stride duration data was obtained from 10 trials, and 9 trials contributed data for hind stance duration as a percent of stride (Table A-5). For the running walk, data was obtained from five to six trials per horse with a total of 21 trials (Table A-6). Stride length increased by 20% and stance duration of the front and hind limbs decreased by about 60% (Table A-7).

A comparison between the mean temporal stride characteristics of the walk and running walk revealed that 3 variables are not significantly different at the walk and running walk, which means that they are velocity-independent stride characteristics; hind stance duration as a percent of total stride time, advance placement as a percent of total stride time and advance lift off as a percent of total stride time (Table A-8). These three variables did not have a significant correlation to velocity or any other velocity dependent temporal variables such as stride length, fore or hind stance duration.

Many of the correlations obtained were intuitive. Velocity was negatively correlated to total stance duration -0.90112, ($P < 0.0001$). If velocity is zero then there is no movement and so stance must be maximal. Stride length was negatively correlated to stance duration; again, this is intuitive. If stride length is zero then stance will be maximum hence no movement.

The comparison of the LCS angles of the left carpal joint at each gait event during the walk and running walk indicated that five of the 12 angles were significantly different (Table 10). The means (degrees) ± sem of the significantly different angles were: hind heel strike about the z axis (-2.6 ± 3.4: 4.0 ± 3.4), front heel strike about the x axis (-10.5 ± 1.4: -18.6 ± 1.7), front heel strike about the z axis (-4.6 ± 2.2: 0.1 ± 2.2), hind toe off about the x axis (3.9 ± 5.8: -4.5 ± 5.6) and front toe off about the x axis (-30.7 ± 3.6: -45.6 ± 4.2) for the walk and running walk respectively $P < 0.05$. The comparison of the LCS angles of the left metacarpophalangeal joint at each gait event during the walk and running walk indicated that two of the 12 angles were significantly different (Table 11). The means (degrees) ± sem of the significantly different angles were: front heel strike about the y axis (11.7 ± 3.2: 4.7 ± 3.6), hind toe off about the y axis (2.1 ± 1.9: -4.9 ± 2.3) for the walk and running walk respectively $P < 0.05$.

## IV. Discussion

In a previous study, the running walk was evaluated at a fast gait and at a slow gait with the mean velocities of 3.8 m/s and 2.66 m/s for fast and slow respectively. Two gait formulas per velocity were generated; fast 56-12, 56-10 and slow, 58-22, 58-18 (Nicodemus *et al.* 2002). Another study on the running walk did not consider velocity but used the horse's trainer and breed association criteria to determine if the horse was performing the proper gait; the gait formulas 53-17 and 53-10 were identified. In the current study, riders were directed to ask their horses to perform the two gaits at the riders preferred velocity and quality. The velocity at the running walk was 3.41 ± 0.13 m/s and generated the gait formula 57-22. The comprehensive gait study that developed the original gait formulas of the running walk described three gait formulas common to the TWH: 54-31, 32-22, and 30-29 (Hildebrand 1965). The results from this study are similar to the results of previous studies of the running walk.

Temporal stride characteristics associated with equine gaits do not fully describe the locomotion patterns associated with different gaits. Within the LCS of the carpal joint the relative angles that differed from the walk to the running walk at the gait events are the same angles that are strongly correlated to stride length, overstride and advance placement. These results should be expected and confirm that some kinematic values associated with the carpal joint of the TWH performing the running walk are different than the kinematic values associated with the carpal joint of the TWH performing the walk.

A long overstride is a desirable characteristic of TWH performance show horses. The increase in overstride accounted for 96% of the increase in stride length; only 4% of the increase in stride length is comprised of an increase in step length. This means that the distance between the hind hoof heel strike and the front hoof heel strike on the same side does not change significantly between the walk and the running walk. A long overstride would seem to be related to the flexibility of the proximal hind limb, the pelvis and possibly the lumbar spine. The hind limb is the primary contributor to overstride in the TWH.

Based on the results of other studies on the running walk, the running walk of the TWH was more similar to the running walk of a 1948 champion Tennessee Walking Horse, the walk of the Quarter Horse, the fast walk of a ranch horse and the paso gait of the Peruvian Paso than it was the running walk as it was performed by the Tennessee Walking Horse in the mid 1960's (Tables A-12, A-13; Hildebrand, 1965; Nicodemus *et al*, 2002; Nicodemus and Clayton, 2003). In a comparison of the gait formulas from this study and three others on the running walk it appears that there is little difference in the gait formulas unless velocity is almost doubled. The two gait formulas of the running walk associated with the highest velocities Hildebrand (1965) are different then the low velocity gait formula described in that study and the gait formulas described in subsequent studies, including this one. This may be a result of differences in methodology and available technology as well as changes in training methods.

The velocity of the running walk in this study never exceeded 5 m/s. Considering the mean velocities and standard deviation at which the running walk was performed in the other two recent studies, it may be safe to conclude that few Tennessee Walking Horses are performing the running walk at the 7 – 9 m/s level seen in the mid 1960's (Hildebrand 1965).

Based on the comparison of data from all four studies, hind stance duration as a percent of total stride time, advance placement as a percent of total stride time, and advance lift off as a percent of total stride time may be suitable characteristics to be used for comparison in a clinical setting. If a clinical exam finds that the velocity-independent variables of a horse differ from these reported values, it may be an indication of lameness. These variables are not breed specific since the walk of the TWH is similar to the walk of the Quarter Horse. It is unknown how lameness would affect the velocity-independent stride characteristics. The front limb characteristics could have a greater difference or be more similar between the walk and the running walk. Or, the hind limb stride characteristics could become different from the walk to the running walk. This study suggests that in order to develop clinically relevant biomechanical models of equine locomotion, that joint specific velocity-independent stride characteristics be identified. This may lead to the ability to associate lameness with an individual joint.

When the hind stance duration as a percent of total stride time, the advance placement as a percent of total stride time, and the advance lift off as a percent of total stride time of the walk were compared with the same characteristics of the running walk, they were found to be similar (Table A-8). The difference seen between the two gaits is a result of a change in front stance duration as a percent of stride (Table A-8). The difference in front stance duration is associated with the increased front limb animation of the running walk (Hildebrand 1965). This would seem to suggest that the animation associated with the front limbs during the walk is not a good indicator of the animation seen in the running walk. This also demonstrates that the running walk is not simply a faster version of the walk. If the running walk was simply a faster version of the walk then there would be an expectation that the front stance duration as a percent of stride would have a similar value at both gaits and would not vary with the change in velocity. If the running walk was simply a faster version of the walk the values of the relative angles of the carpal joint and the fetlock joint should be similar in value at the same gait event during the two gaits. Since these differences exist, it can be concluded that the running walk as performed in this study is not the same gait as the walk.

Use of velocity independent variables may make comparisons of gaits among horses possible even when the velocity among the horses is significantly different or cannot be controlled.

# IV. Experimental Considerations

The original fifteen horses used in this study were not the property of the university and were brought in daily by owners that had volunteered their horses for the study. The first six horses were used to develop an acceptable layout that would allow the largest data collection area, maintain high camera resolution and be safe for the horses, riders and equipment. Several marker cluster arrangements were used until cluster arrangements were found that were easily tracked, fit the design parameters (see chapter 1), and remained on the horse without interfering with movement.

Since the camera layout and marker clusters had been established data from horse number 7 was expected to be usable; this horse was also horse number 1 and had been through the process once already. Unfortunately during the reconstruction process the data was seen to have large gaps in the trials. Even after running the data through a variety of different reconstruction parameters the data was deemed un-useable. This was also the case for horse 8. All data from horse 5 was lost when the equipment overheated and shut-down. During the data collection process horse 11 was identified as being lame and was immediately removed from the study. According to the owner the horse was under veterinary care and it was believed that the lameness issue had been resolved. Data from horses 12, 13, and 14 had large gaps in the data. This was a result of the reflective markers developing a film from the soil from the track. This issue was resolved for horses 15 and 16 which generally provided useable data. The running walk trial from horse 15 was not used because it was determined that the horse was not performing a running walk. There was no advance placement or advance lift off; the horse was pacing. Horses 9, 10, 15, and 16 contributed to the final data.

## V. Conclusion

The adaptation of the currently available human gait analysis technology for use in equine gait analysis has proven to be both practicable and beneficial. Highly invasive methods can be replaced with accurate non-invasive techniques, CAST and PCT. These techniques may permit the rapid development of clinically relevant standards for the detection of sub-clinical lameness and provide a means to predict future performance.

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# Appendix

**Table A-1: Body Segments and Joints Tracked During Data Collection**

| Body Segments | Joints |
| --- | --- |
| Head * | Carpal joint |
| Neck | Metacarpophalangeal joint |
| Trunk | Proximal interphalangeal joint of the fore limb |
| Lumbar | Tarsal joint |
| Sacrum | Tarsocrural joint |
| Left Humerus | Proximal interphalangeal joint of the hind limb |
| Left Radius | |
| Left Metacarpus | |
| Left Fore Pastern/hoof | |
| Pelvis | |
| Left Femur | |
| Left Tibia | |
| Left Metatarsus | |
| Left Hind Pastern/hoof | |

* The head was tracked with five individual markers (not an array).

**Table A-2: Marker Sets**

| Static Marker Set | | Dynamic Marker Set | |
|---|---|---|---|
| **Label** | **Location** | **Label** | **Location** |
| LTEM | Left temporal bone | LTEM | Left temporal bone |
| RTEM | Right temporal bone | RTEM | Right temporal bone |
| LATL | Atlas left | LATL | Atlas left |
| RATL | Atlas right | RATL | Atlas right |
| POLL | Top of head poll | POLL | Top of head poll |
| LCT1 | Upper left cervical spine | LCT1 | Upper left cervical spine |
| LCT2 | Lower left cervical spine | LCT2 | Lower left cervical spine |
| LCT3 | Lower right cervical spine | LCT3 | Lower right cervical spine |
| LCT4 | Upper right cervical spine | LCT4 | Upper right cervical spine |
| LC7 | Cervical7 left | | |
| RC7 | Cervical7 right | | |
| LSAD1 | Upper left saddle | LSAD1 | Upper left saddle |
| LSAD2 | Lower left saddle | LSAD2 | Lower left saddle |
| LSAD3 | Lower right saddle | LSAD3 | Lower right saddle |
| LSAD4 | Upper right saddle | LSAD4 | Upper right saddle |
| LUM3 | Lumbar3 | LUM3 | Lumbar3 |
| LUM5 | Lumbar5 | LUM5 | Lumbar5 |
| SAC3 | Sacral3 | SAC3 | Sacral3 |
| SAC5 | Sacral5 | SAC5 | Sacral5 |
| TAIL2 | Caudal2 | TAIL2 | Caudal2 |
| LLSHLD | Shoulder left lateral | LLSHLD | Shoulder left lateral |
| LHUM | Mid humerus | LHUM | Mid humerus |
| LLELB | Elbow left lateral | LLELB | Elbow left lateral |
| LRAD1 | Upper left radius | LRAD1 | Upper left radius |
| LRAD2 | Lower left radius | LRAD2 | Lower left radius |
| LRAD3 | Lower right radius | LRAD3 | Lower right radius |
| LRAD4 | Upper right radius | LRAD4 | Upper right radius |
| LLCARP | Carpus left lateral | | |
| LMCARP | Carpus left medial | | |
| LMCP1 | Upper left metacarpus | LMCP1 | Upper left metacarpus |
| LMCP2 | Lower left metacarpus | LMCP2 | Lower left metacarpus |
| LMCP3 | Lower right metacarpus | LMCP3 | Lower right metacarpus |
| LMCP4 | Upper right metacarpus | LMCP4 | Upper right metacarpus |
| LLFFET | Fetlock fore left lateral | LLFFET | Fetlock fore left lateral |
| LMFFET | Fetlock fore left medial | | |
| LFPST1 | Fore pastern left upper | LFPST1 | Fore pastern left upper |

**Table A-2 continued:**

| Static Marker Set | | Dynamic Marker Set | |
|---|---|---|---|
| **Label** | **Location** | **Label** | **Location** |
| LFPST2 | Fore pastern left lower | LFPST2 | Fore pastern left lower |
| LLFCOR | Coronary fore left lateral | LLFCOR | Coronary fore left lateral |
| LMFCOR | Coronary fore left medial | | |
| LLFH | Fore hoof left lateral | LLFH | Fore hoof left lateral |
| LFHMT | Fore hoof left mid toe | LFHMT | Fore hoof left mid toe |
| LTUBC | Tuber coxae left | LTUBC | Tuber coxae left |
| RTUBC | Tuber coxae right | | |
| LGTRO | Greater trocanter left | LGTRO | Greater trocanter left |
| LTUBI | Tuber ischii left | LTUBI | Tuber ischii left |
| LTH2 | Lower left thy | LTH2 | Lower left thy |
| LTH3 | Upper right thy | LTH3 | Upper right thy |
| LSK1 | Upper left shank | LSK1 | Upper left shank |
| LSK2 | Lower left shank | LSK2 | Lower left shank |
| LSK3 | Lower right shank | LSK3 | Lower right shank |
| LSK4 | Upper right shank | LSK4 | Upper right shank |
| LLTS | Tarsus left lateral | | |
| LMTS | Tarsus left medial | | |
| LMT1 | Upper left metatarsus | LMT1 | Upper left metatarsus |
| LMT2 | Lower left metatarsus | LMT2 | Lower left metatarsus |
| LMT3 | Lower right metatarsus | LMT3 | Lower right metatarsus |
| LMT4 | Upper right metatarsus | LMT4 | Upper right metatarsus |
| LLHFET | Fetlock hind left lateral | LLHFET | Fetlock hind left lateral |
| LMHFET | Fetlock hind left medial | | |
| LHPST1 | Hind pastern left upper | LHPST1 | Hind pastern left upper |
| LHPST2 | Hind pastern left lower | LHPST2 | Hind pastern left lower |
| LLHCOR | Coronary hind left lateral | LLHCOR | Coronary hind left lateral |
| LMHCOR | Coronary hind left medial | | |
| LLHH | Hind hoof left lateral | LLHH | Hind hoof left lateral |
| LHHMT | Hind hoof left mid toe | LHHMT | Hind hoof left mid toe |

**Table A-3: Temporal Stride Characteristics Associated with the Walk and the Running Walk**

| **Temporal Stride Characteristics** | |
|---|---|
| Velocity, m/s | Hind Stance Duration, sec |
| Total Stride Duration, sec | Hind Stance % of Total Stride |
| Front Stride Duration, sec | Total Stance, sec |
| Hind Stride Duration, sec | Lateral Advance Lift Off % of Total Stride |
| Stride Length, meters | Lateral Advance Placement % of Total Stride |
| Front Stance Duration, sec | Overstride, meters |
| Front Stance (% of Total Stride) | |

**Table A-4: Mean Body Segment Lengths (m) and Hoof Angles (deg).**

| Body Segment | n | Mean ± SEM | Minimum | Maximum |
|---|---|---|---|---|
| **Body Length** | 4 | 1.67 ± 0.048 | 1.6 | 1.8 |
| **Girth** | 4 | 1.73 ± 0.048 | 1.6 | 1.8 |
| **Cervical Spine** | 4 | 0.56 ± 0.008 | 0.54 | 0.58 |
| **Humerus** | 3 | 0.25 ± 0.011 | 0.23 | 0.27 |
| **Radius** | 4 | 0.44 ± 0.015 | 0.44 | 0.49 |
| **Metacarpus** | 4 | 0.27 ± 0.012 | 0.24 | 0.3 |
| **Front Pastern** | 4 | 0.14 ± 0.006 | 0.13 | 0.16 |
| **Femur** | 3 | 0.26 ± 0.004 | 0.25 | 0.26 |
| **Tibia** | 4 | 0.58 ± 0.03 | 0.49 | 0.63 |
| **Metatarsus** | 4 | 0.36 ± 0.007 | 0.35 | 0.38 |
| **Hind Pastern** | 4 | 0.12 ± 0.015 | 0.09 | 0.14 |
| **Left Front Toe Length** | 4 | 3.34 ± 0.011 | 2.63 | 3.76 |
| **Left Front Toe Angle** | 4 | 55.5 ± 3.316 | 50.85 | 65.11 |
| **Left Front Heel Length** | 4 | 1.59 ± 0.133 | 1.43 | 1.99 |
| **Left Front Heel Angle** | 4 | 54.24 ± 4.354 | 43.67 | 64.79 |
| **Left Hind Toe Length** | 4 | 3.26 ± 0.16 | 2.79 | 3.47 |
| **Left Hind Toe Angle** | 4 | 57.32 ± 1.079 | 54.57 | 59.84 |
| **Left Hind Heel Length** | 4 | 1.07 ± 0.146 | 0.82 | 1.46 |
| **Left Hind Heel Angle** | 4 | 47.48 ± 3.214 | 37.91 | 51.57 |

* n = number of segments

**Table A-5: Temporal Stride Characteristics of the Walk Performed by the Tennessee Walking Horse.**

| Stride Characteristics | Total Number of Strides | Mean ± SEM |
|---|---|---|
| **Velocity, m/s** | 19 | 1.77 ± 0.10 |
| **Total Stride Duration, sec** | 16 | 1.065 ± 0.04 |
| **Stride Length, meters** | 18 | 1.79 ± 0.03 |
| **Front Stance Duration, sec** | 16 | 0.76 ± 0.03 |
| **Front Stance % of Stride** | 12 | 67.8 ± 2.7 |
| **Hind Stance Duration, sec** | 17 | 0.74 ± 0.02 |
| **Hind Stance % of Stride** | 14 | 69 ± 2.8 |
| **Total Stance, sec** | 17 | 0.99 ± 0.03 |
| **Advance Lift Off % of Stride** | 14 | 24.7 ± 1.7 |
| **Advance Placement % Stride** | 15 | 21.5 ± 1.2 |
| **Overstride, meters** | 17 | 0.34 ± 0.04 |

**Table A-6: Temporal Stride Characteristics Of The Running Walk Performed By The Tennessee Walking Horse.**

| Stride Characteristics | Total Number of Strides | Mean ± SEM |
|---|---|---|
| **Velocity, m/s** | 15 | 3.41 ± 0.13 |
| **Total Stride Duration, sec** | 13 | 0.68 ± 0.11 |
| **Stride Length, meters** | 13 | 2.11 ± 0.11 |
| **Front Stance Duration, sec** | 19 | 0.33 ± 0.06 |
| **Front Stance % of Stride** | 11 | 48 ± 0.07 |
| **Hind Stance Duration, sec** | 13 | 0.34 ± 0.02 |
| **Hind Stance % of Stride** | 10 | 52 ± 0.05 |
| **Total Stance, sec** | 12 | 0.44 ± 0.03 |
| **Advance Lift Off % Stride** | 12 | 16 ± 8 |
| **Advance Placement % Stride** | 15 | 18 ± 8 |
| **Overstride, meters** | 14 | 0.68 ± 0.04 |

**Table A-7: Comparison Of Temporal Stride Characteristics Of The Walk And Running Walk.**

| Gait Parameter of Interest | n | Walk | Running Walk | |
|---|---|---|---|---|
| | | Mean ± SEM | 3.41 ± 0.13 | P |
| Velocity, m/s | 34 | 1.77 ± 0.10 | 0.68 ± 0.11 | <0.0001 |
| Total Stride Duration, sec | 29 | 1.065 ± 0.04 | 2.11 ± 0.11 | <0.0001 |
| Stride Length, meters | 31 | 1.79 ± 0.03 | 0.33 ± 0.06 | <0.0001 |
| Front Stance Duration, sec | 30 | 0.76 ± 0.03 | 48 ± 0.07 | <0.0001 |
| Front Stance % of Stride | 23 | 67.8 ± 2.7 | 0.34 ± 0.02 | <0.0006 |
| Hind Stance Duration, sec | 30 | 0.74 ± 0.02 | 52 ± 0.05 | <0.0001 |
| Hind Stance % of Stride | 24 | 69 ± 2.8 | 0.44 ± 0.03 | ns |
| Total Stance, sec | 29 | 0.99 ± 0.03 | 16 ± 8 | <0.0001 |
| Advance Lift Off % Stride | 23 | 24.7 ± 1.7 | 18 ± 8 | ns |
| Advance Placement % Stride | 30 | 21.5 ± 1.2 | 0.68 ± 0.04 | ns |
| Overstride, meters | 31 | 0.34 ± 0.04 | 3.41 ± 0.13 | <0.0001 |

*Means in the same row with different superscripts are significantly different. n = strides

**Table A-8: Correlations of Temporal Stride Characteristics**

| Stride Characteristics | Condition W/RW | Velocity, m/s | Stride, sec | Stride Length, m | Front Stance, sec | Front Stance (% of Stride, sec) | Hind Stance Duration | Total Stance, sec |
|---|---|---|---|---|---|---|---|---|
| **Total Stance , sec** | -0.89*;n=28 | -0.90*;n=28 | 0.91*;n=23 | -0.75*;n=25 | 0.98*;n=27 | 0.81*;n=19 | 0.97*;n=29 | |
| **Advance Lift Off** | -0.71*;n=29 | -0.70*;n=28 | 0.75*;n=23 | ns | 0.88*;n=27 | 0.74*;n=19 | 0.82*;n=29 | 0.89*;n=31 |
| **Adv. Lift Off (% of Stride, sec)** | ns | ns | ns | ns | ns | ns | ns | ns |
| **Advance Placement, sec** | -0.72*;n=29 | -0.73*;n=29 | 0.71*;n=24 | -0.71*;n=25 | 0.84*;n=27 | 0.71*;n=19 | 0.87*;n=29 | 0.90*;n=29 |
| **Adv. Lift Off (% of Stride, sec)** | ns | ns | ns | ns | ns | ns | ns | ns |
| **Overstride, m** | 0.72*;n=29 | 0.71*;n=29 | ns | 0.87*;n=24 | -0.71;n=25 | ns | -0.73*;n=28 | -0.74*;n=27 |
| **Overstride % Stride Length, m** | ns | ns | | 0.81*;n=24 | | | | -0.72*;n=23 |
| **Stride Length, m** | 0.77*;n=27 | 0.82*;n=26 | | | | | | |
| **Front Stance, sec** | -0.91*;n=28 | -0.87*;n=28 | 0.94*;n=22 | -0.73*;n=24 | | | | |
| **Front Stance (% of Stride, sec)** | -0.71*;n=19 | ns | ns | ns | 0.81*;n=18 | | | |
| **Hind Stance, sec** | -0.95*;n=30 | -0.92*;n=29 | 0.89*;n=23 | -0.76*;n=25 | 0.96*;n=27 | 0.79*;n=19 | | |
| **Hind Stance (% of Stride, sec)** | ns | ns | ns | ns | ns | ns | ns | ns |
| **Stride Duration, sec** | -0.80*;n=25 | -0.95*;n=25 | | | 0.94*;n=22 | | | 0.91*;n=23 |

* P < 0.05, n = number of strides

**Table A-9: Correlations Among the Local Coordinate System of the Carpal Joint, Stride Length, Advance Lift Off, Advance Placement and Overstride**

| Stride Characteristics | Advance Lift Off, sec | Overstride, m | cjafhsx | cjafhsy | cjafhsz | cjaftox | cjahtox |
|---|---|---|---|---|---|---|---|
| **Stride Length, m** | | | -0.75*;n=23 | | | -0.75*;n=20 | -0.72*;n=23 |
| **Overstride, m** | | | -0.76*;n=27 | | 0.81*;n=27 | -0.70*;n=22 | -0.74*;n=27 |
| **Advance Placement, sec** | 0.84*;n=29 | -0.75*;n=28 | 0.74*;n=25 | | | | 0.71*;n=20 |
| **cjahtox** | | | 0.80*;n=27 | | | | |
| **cjahtoy** | | | | 0.99*;n=27 | | | |
| **cjahtoz** | | | | | 0.84*;n=27 | | |

* P < 0.05; n = number of strides, carpal joint angle (cja), hind toe off (hto), front toe off (fto), front heel strike (fhs)

**Table A-10: A Comparison of the Local Coordinate System Angles of the Left Carpal Joint at Each Gait Event During the Walk and Running Walk.**

| | | Walk | Running Walk | |
|---|---|---|---|---|
| **Carpal Joint Angle** | **n** | **Mean ± sem** | **Mean ± sem** | **P value** |
| Hind Heel Strike X | 30 | -66.2$^A$ ± 4.3 | -69.2$^A$ ± 4.9 | ns |
| Hind Heel Strike Y | 30 | 18.3$^A$ ± 4.1 | 17.3$^A$ ± 4.0 | ns |
| Hind Heel Strike Z | 30 | -2.6$^B$ ± 3.4 | 4.0$^A$ ± 3.4 | 0.0068 |
| Front Heel Strike X | 31 | -10.5$^A$ ± 1.4 | -18.6$^B$ ± 1.7 | 0.0009 |
| Front Heel Strike Y | 31 | 21.7$^A$ ± 5.1 | 19.8$^A$ ±5.2 | ns |
| Front Heel Strike Z | 31 | -4.6$^B$ ± 2.2 | 0.1$^A$ ± 2.2 | 0.0003 |
| Hind Toe Off X | 30 | 3.9$^A$ ± 5.8 | -4.5$^B$ ± 5.6 | 0.0141 |
| Hind Toe Off Y | 30 | 21.7$^A$ ± 5.9 | 21.9$^A$ ± 5.6 | ns |
| Hind Toe Off Z | 30 | 2.1$^A$ ± 2.4 | 4.6$^A$ ± 2.4 | ns |
| Front Toe Off X | 26 | -30.7$^A$ ± 3.6 | -45.6$^B$ ± 4.2 | 0.0141 |
| Front Toe Off Y | 26 | 22.1$^A$ ± 4.3 | 20.8$^A$ ± 4.5 | ns |
| Front Toe Off Z | 26 | 8.6$^A$ ± 2.8 | 8.2$^A$ ± 3.0 | ns |

**Table A-11: A Comparison of the Local Coordinate System Angles of the Metacarpophalangeal Joint at Each Gait Event during the Walk and Running Walk.**

| | | Walk | Running Walk | |
|---|---|---|---|---|
| **Front Fetlock Joint Angle** | **n** | **Mean ± sem** | **Mean ± sem** | **P value** |
| Hind Heel Strike X | 23 | -0.3$^A$ ± 19.3 | -3.7$^A$ ±20.0 | ns |
| Hind Heel Strike Y | 23 | 9.4$^A$ ± 6.1 | 3.6$^A$ ± 6.5 | ns |
| Hind Heel Strike Z | 18 | -5.2$^A$ ± 2.9 | 1.3$^A$ ± 3.6 | ns |
| Front Heel Strike X | 26 | 18.5$^A$ ± 18.6 | 39.2$^A$ ± 20.5 | ns |
| Front Heel Strike Y | 26 | 11.7$^A$ ± 3.2 | 4.7$^B$ ± 3.6 | 0.004 |
| Front Heel Strike Z | 26 | -22.7$^A$ ±10.4 | -15.4$^A$ ± 12.0 | ns |
| Hind Toe Off X | 25 | 49.4$^A$ ± 17.4 | 64.2$^A$ ± 17.7 | ns |
| Hind Toe Off Y | 25 | 2.1$^A$ ± 1.9 | -4.9$^B$ ±2.3 | 0.0311 |
| Hind Toe Off Z | 25 | -10.7$^A$ ± 3.0 | -4.7$^A$ ± 3.7 | ns |
| Front Toe Off X | 24 | 29.1$^A$ ± 18.8 | 49.0$^A$ ± 20.7 | ns |
| Front Toe Off Y | 24 | 15.6$^A$ ± 5.3 | 12.6$^A$ ± 5.9 | ns |
| Front Toe Off Z | 24 | -7.6 $^A$ ± 3.0 | -1.4$^A$ ± 3.8 | ns |

**Table A-12: A Comparison of Three Velocity Independent Variables of the Walk and Running Walk**

| Study | Gait | n | | Velocity | Lateral Advance Placement % Stride | Lateral Advance Lift Off % Stride | Hind Stance % Stride | Stride Duration, ms |
|---|---|---|---|---|---|---|---|---|
| | | Strides/ Horse | Horses | Mean ± SEM | Mean ± SEM | Mean ± SEM | Mean ± SEM | Mean ± SEM |
| Nicodemus, M., Holt, Swartz, 2002 | RW | 6 | 6 | 3.8 ± 0.18 | 12 ± 3 | 10 ± 2 | 56 ± 2 | 683 ± 12 |
| | RW | 6 | 6 | 2.66 ± 0.34 | 22 ± 2 | 18 ± 4 | 58 ± 3 | 753 ± 38 |
| Nicodemus, M., Clayton, 2003 | RW | 5 | 3 | Not Reported | 17 ± 7 | 10 ± 5 | 53 ± 5 | 678 ± 44 |
| Present Study | RW | 2-4 | 3 | 3.41 ± 0.14 | 22 ± 2 | 19 ± 3 | 57 ± 4 | 651 ± 4 |
| | W | 4-6 | 4 | 1.77 ± 0.13 | 22 ± 2 | 19 ± 3 | 66 ± 2 | 1.07 ± 4 |

*When reported, only velocity was significantly different.

**Table A-13: A Comparison of the Gait Formulas From Four Studies of The Walk and Running Walk.**

| Study | Gait | n | | Velocity, m/s | | | |
|---|---|---|---|---|---|---|---|
| | | Strides/Horse | Horses | Mean ± SEM | Gait Formulas | | |
| **Hildebrand, M. 1965** | **RW** | na | 11 | na | 54-31 | 32-22 | 30-29 |
| **Nicodemus, M., Holt, Swartz, 2002** | **RW** | 6 | 6 | 3.8 ± 0.18 | 56-12 | 56-10 | |
| | **RW** | 6 | 6 | 2.66 ± 0.34 | 58-22 | 58-18 | |
| **Nicodemus, M., Clayton, 2003** | **RW** | 5 | 3 | na | 53-17 | 53-10 | |
| **Present Study** | **RW** | 2-4 | 3 | 3.41 ± 0.14 | 57-22 | 57-19 | |
| | **W** | 4-6 | 4 | 1.77 ± 0.13 | 66-22 | 66-19 | |

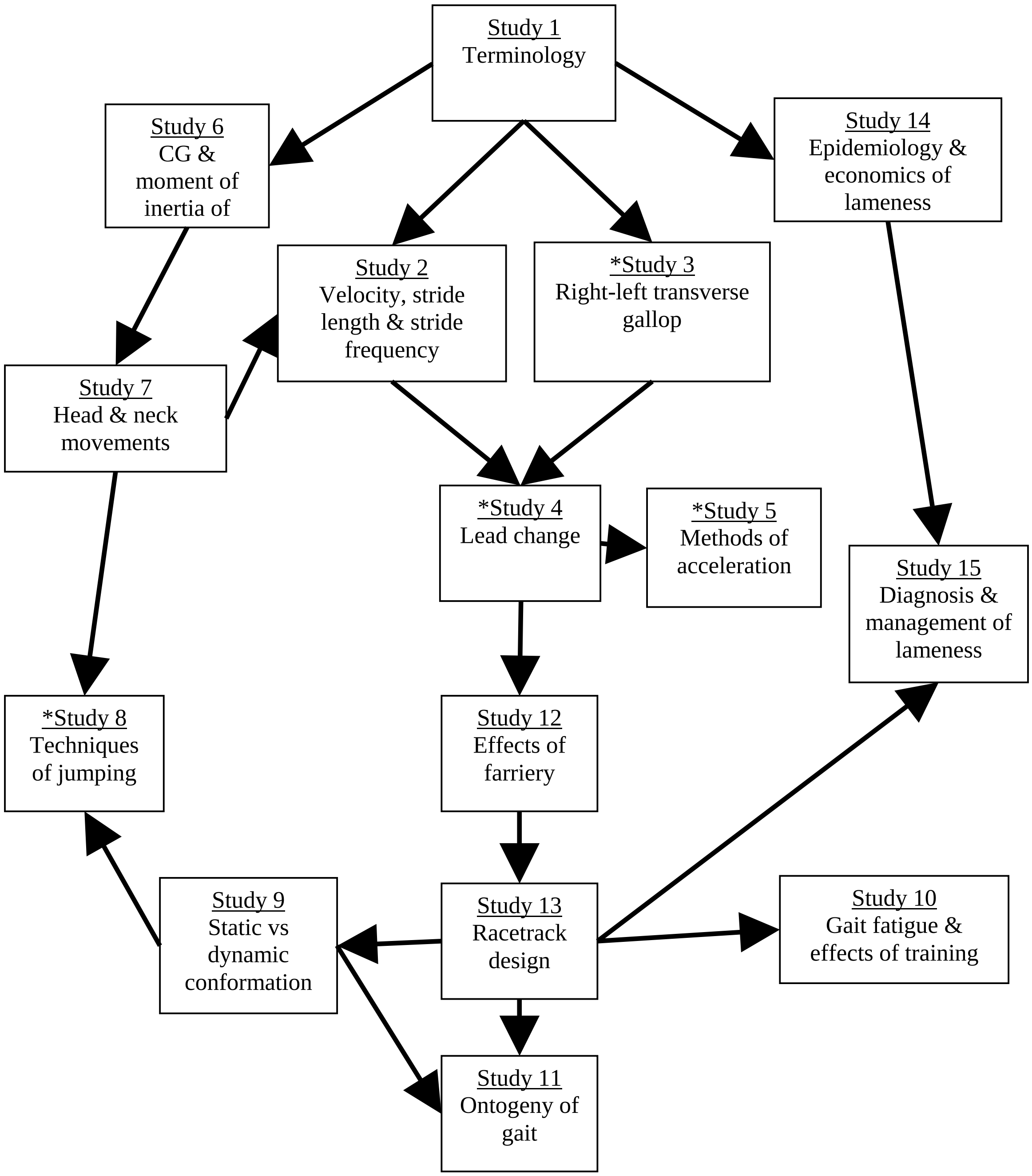
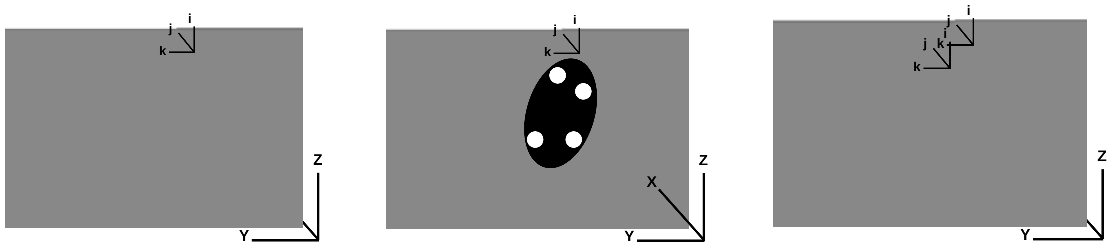
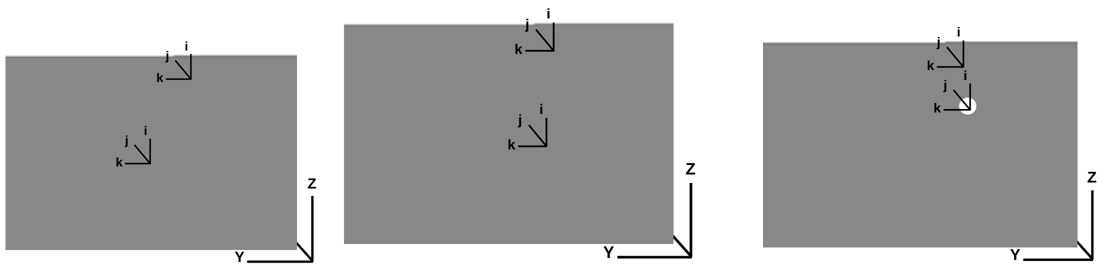


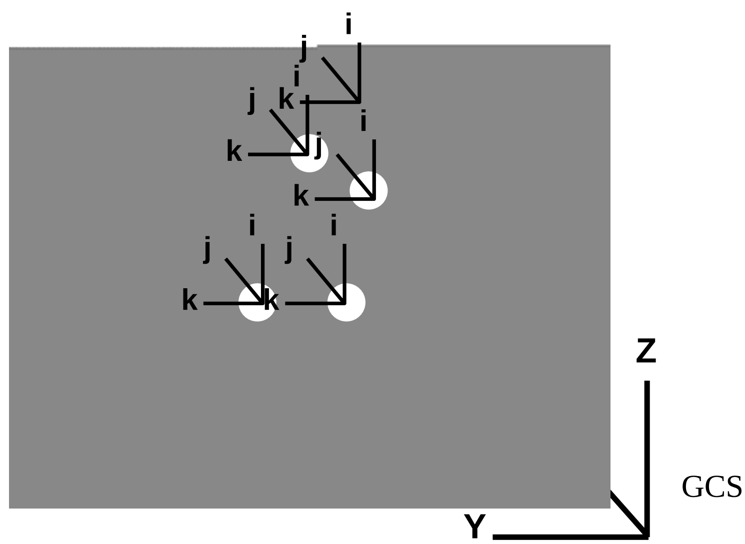

**Figure A-1: "Suggested order of research into locomotion for the Thoroughbred horse" from (Leach and Crawford 1983)** *Omitted from Standardbred research focus areas.



2a. GCS and LCS 2b. GCS, LCS and rigid form 2c. GCS and LCS and TF1



2d. GCS and LCS and TF2 2e. GCS and LCS and TF3 2f. GCS and LCS and TF4




**Figures A-2a through A-2g: A body segment with a bone embedded frame.**

2g. Estimated anatomical frame created by marker cluster. The anatomical frame is an estimate of the LCS. Also demonstrated is the redundancy of the technical frames (TF) that are created by the marker cluster. Marker cluster is removed after fig. 2b for clarity.

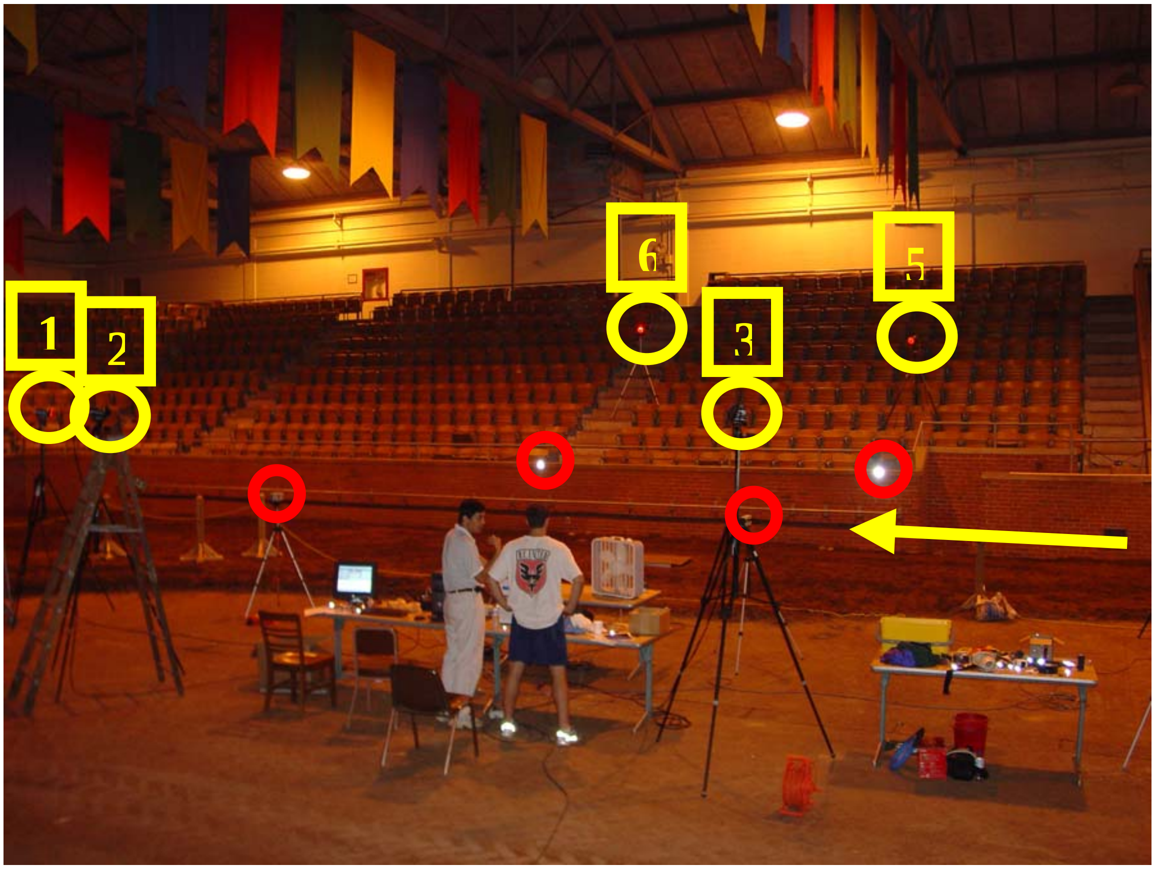



**Figure A-3: Laboratory Environment.**

The numbers indicate the orientation and labeling of the cameras. Camera 4 is just out of frame to the right of camera #3. The small circles indicate the location of the timers and removable reflective markers. The arrow indicates the direction the horses traveled during data collection.

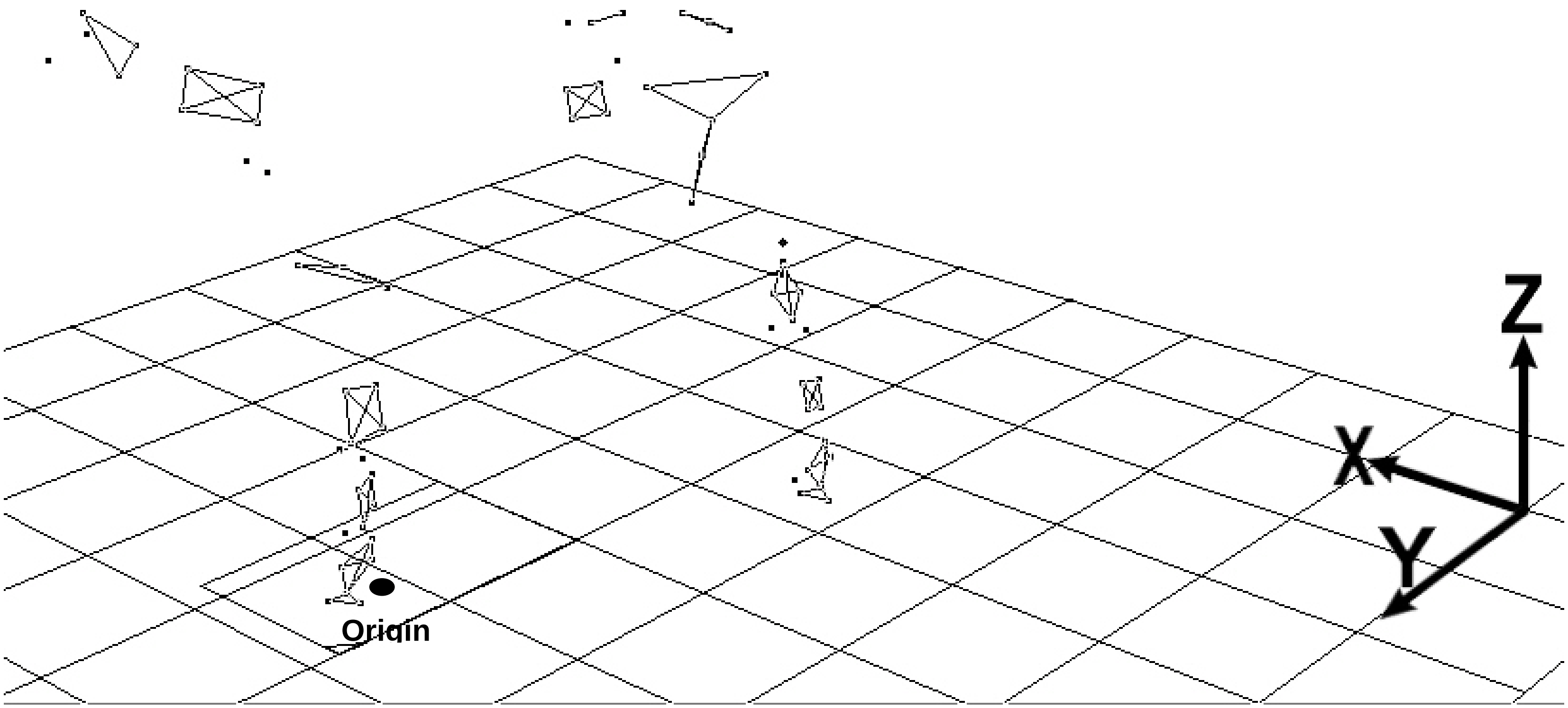



**Figure A-4: The Lab Coordinate System Showing Static And Anatomical Markers.** Arrows point towards positive values of the global coordinate system. The origin is established during static camera calibration through the use of the L-frame

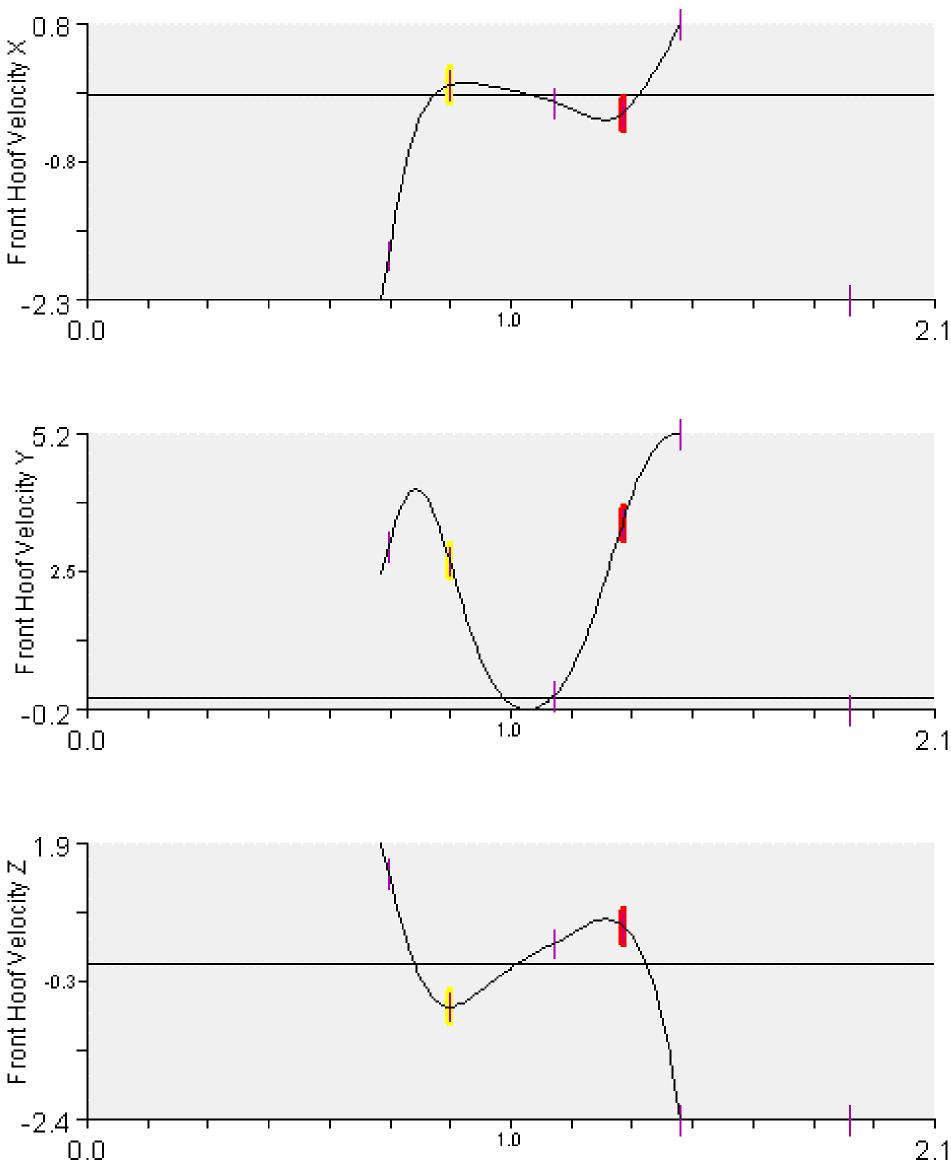



**Figure A-5: Graphs of Front Hoof Velocities in All Three Axes.** Bolded marks on line are left front heel strike and left front toe off (left to right).

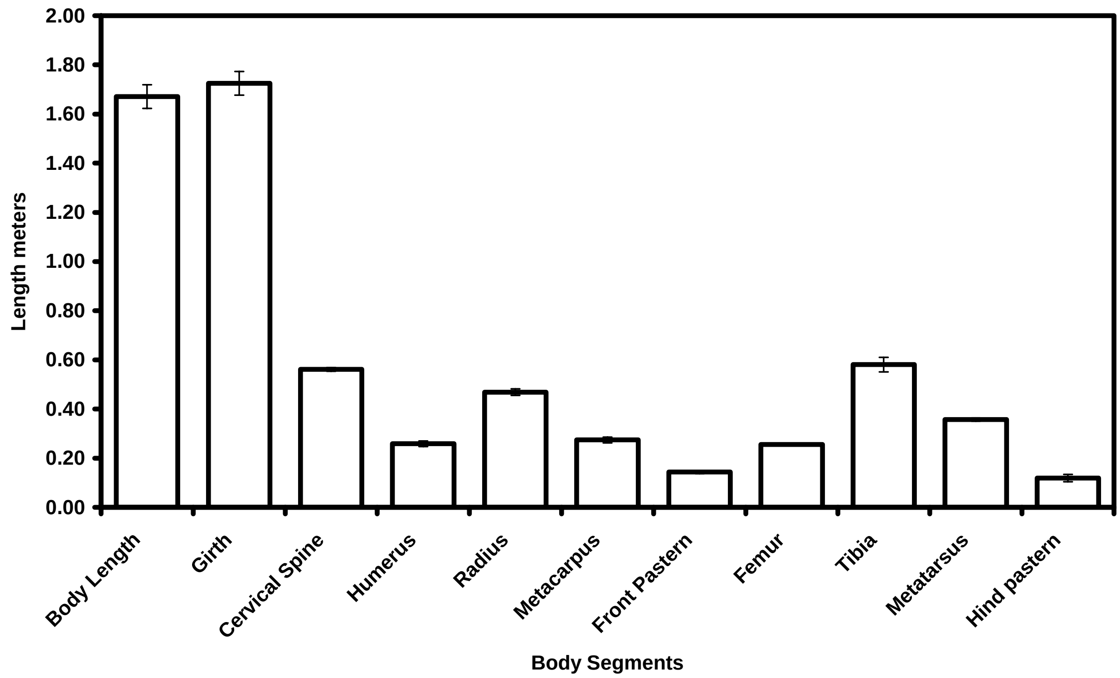



**Figure A-6: Mean with Error Bars for Body Segment Lengths of the Four Horses that Provided Motion Data.**

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|---|---|
| **Abduction** | Away from the midline of the body. |
| **Adduction** | Towards the midline of the body. |
| **Advance lift off** | The time or distance between hind hoof toe off and a front hoof toe off during a single stride. This applies to foot falls of the same stride. |
| **Advance placement** | The time or distance between hind hoof ground contact and a front hoof ground contact during a single stride. This applies to foot falls of the same stride. |
| **Anatomical marker** | Used to identify a specific anatomic location on a body segment and orient tracking markers. Generally removed during dynamic data collection trials, although it may also be used as a tracking marker in limited cases. |
| **Anatomical frame** | An estimation of the LCS, derived from three or more technical frames. |
| **Body segment length** | The distance between the proximal joint center and the distal joint center of a body segment. |
| **Extension** | A movement that increases the angle between two adjacent body parts. |
| **External rotation** | Rotation away from the midline of the body. |
| **Flexion** | A movement that decreases the angle between two adjacent body parts. |
| **Gait event** | A regular occurrence of the foot fall during a step: heel strike, toe off |
| **Gallop** | A four beat running gait that can occur with either of these support sequences: LH, RH, RF, LF (rotary gallop); LH, RH, LF, RF (transverse gallop). |
| **GCS** | Global coordinate system. Allows for three dimensional orientations in relation to the vertical, anterior/posterior and medial/lateral axes. |
| **Head nod** | The vertical movement of the head associated with the running walk. |
| **Heel strike** | The point at which the heel first contacts the ground, signaling the end of the swing phase and the beginning of the stance phase of a stride. |
| **Internal rotation** | Rotation towards the midline of the body |
| **Joint center** | The single point in common of two joint segments, the origin of axes of the angle made by two joint segments. |
| **Kinematics** | The study of movement without regard to the contributing forces. |

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| **LCS** | Local coordinate system. The application of three axes to a body segment where positive Z is the long axes of the segment, positive Y is the posterior to anterior direction, and positive X is the medial to lateral direction and the origin of the axes is the center of mass of the segment. |
| **LF** | Left front hoof |
| **LH** | Left hind hoof |
| **Marker** | A 14 millimeter acrylic sphere covered with 3M reflective tape and threaded onto a plastic base. |
| **Marker array** | A non-collinear grouping of two or more markers affixed to a rigid base, used as tracking markers. Present during static and dynamic data collection trials |
| **Marker tracking** | A single marker or an array used during dynamic data collection to orient a body segment. |
| **Marker virtual** | A computer generated marker used to identify body segment locations when an anatomical marker may not be practical. |
| **Midline** | An imaginary vertical line or plane that transects the body into four parts; front, back, left and right |
| **Overstride** | The time or distance between front hoof toe off and hind hoof heel strike on the same side. Overstride is a component and continuation of the previous full stride *This should not be confused with advanced placement or advance lift off.* |
| **Pace** | A symmetrical gait where the legs on the same side of the horse move together. |
| **RF** | Right front hoof |
| **RH** | Right hind hoof |
| **Rotational movement** | Movement about an axis. |
| **Running walk** | A distinct 4 beat symmetrical gait performed by the TWH. With the support sequence of LH, LF, RH, RF. |
| **Segment coordinate system** | The application of three axes to a body segment where Z is the long axes of the segment, Y is the posterior to anterior direction, and X is the medial to lateral direction and the origin of the axes is the distal joint center. |
| **Stance phase** | A step. From heel strike to toe off of a hoof. This can also be related to several hooves with simultaneous ground contact. |
| **Stepping gait** | A four beat gait with no suspension phase in the stride. |

| | |
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| **Stride** | The point from the occurrence of a gait event to the point that it occurs again. |
| **Stride duration** | The time for the completion of one stride. |
| **Stride length** | The distance covered during one stride. |
| **Support sequence** | The order that hoofs contact the ground during a stride. |
| **Suspension phase** | No contact with the ground by any hoofs. |
| **Swing phase** | The portion of the stride when the hoof is not in contact with the ground. |
| **Technical frame** | Coordinate system described by the location of tracking markers. In conjunction with other technical frames it defines the anatomical frame |
| **Toe off** | The point at which the toe of a hoof leaves the ground, signaling the end of the stance phase and the beginning of the swing phase. |
| **Translational movement** | Movement along an axis. |
| **Trot** | A symmetrical gait where diagonal pairs of hoofs move in unison, LH/RF, RH/LF. |
| **TWH** | Tennessee Walking Horse |
| **Walk** | A four beat gait common to all quadrupeds. With the support sequence of LH, LF, RH, RF. |

# VITA

Paul Roberson was born at Fort Rucker in Montgomery, Alabama in 1958. He attended 7 schools in 5 states before graduating from Red Wing Central High School in Red Wing MN. In 1976 he entered the United States Navy where he received training as a marine diesel mechanic and training as a drug and alcohol rehabilitation representative.

After leaving the Navy in 1980, he worked as a bartender and became a beverage manager for Radisson hotels. In 1985 he began working as a department manager for Herman's World of Sporting Goods in Miami FL. In 1987 he became a store manager, working in store with more than $4 million in annual sales. Herman's sold off its retail units and Paul made a major change in his career.

In 1992 he attended the Kentucky Horseshoeing School under the direction of Mitch Taylor MS, CJF. Paul returned to Florida just prior to the arrival of Hurricane Andrew. Unable to develop a farrier business among the devastation he volunteered his skills at Tropical Park in Miami. More than 200 critical care horses were being stabled there. This proved to be a highlight in his education as a farrier. He was given the opportunity to work with veterinarians from around the country on lameness issues that the average farrier never sees, shortly there after he moved to Knoxville, TN.

From 1994 until 1999 Paul volunteered as a farrier for Shangri-La Therapeutic Academy of Riding (STAR). In 1999 an automobile accident left him with injuries that prevented him from continuing to shoe horses for a living. Paul began his college career at Pellissippi State Community College and in 2004 received a Bachelor’s of Science Degree in Animal Science with a concentration in science and technology from the University of Tennessee. Paul is a guest lecturer in the horse production classes at the University of Tennessee and continues to speak to horse clubs and 4-H groups about the role of the farrier and hoof care. He continued to volunteer at STAR and served in several capacities on the Board of Directors, including 2 years as President. Paul is also a founding member and past 3 term President of the East Tennessee Farriers Association and remains an active member.