CHANGES IN CONFORMATION AND WALK KINEMATICS OF SUCKLING AND WEANLING WARMBLOOD FOALS

Sarah F. Denham

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the degree of

Master of Science
In
Animal and Poultry Sciences

Rebecca K. Splan, Chair
W. Burt Staniar
John J. Dascanio

September, 6th 2007
Blacksburg, VA

Key Words: Growth, conformation, development, equine biomechanics, foal, warmblood

Changes in Conformation and Walk Kinematics of Suckling
and Weanling Warmblood Foals

Sarah F. Denham

ABSTRACT

The objectives of these two studies were to characterize normal growth and resultant changes in conformation and walk kinematics of warmblood foals. The first study quantified linear and angular conformation changes of 13 warmblood foals during the first 9 mo of growth. An objective photographic method of evaluating conformation was used to obtain all data. All linear measurements increased significantly over the investigated ages and growth rates were highest in the first 2 mo of growth. Total percentage of growth during the study was greatest for neck and back length. Distal limb growth was minimal over the investigated ages. Metacarpal growth slowed earlier than many other traits. Length of the metatarsus increased minimally during the studied ages with significant growth occurring only between 23 wk and post-weaning measurements. Increasing wither heights were positively associated with increases in scapula, humerus, radius, ilium, femur, tibia and metatarsal and metacarpal lengths. Angular conformation also changed significantly during growth. Trends in angular changes were generally less clear than those for linear variables. Scapula, femur and hock angles significantly increased and humerus angle decreased with age. Utilizing a plumb line from the hock upward, the distance of the hindlimb behind the body was quantified. The distance out behind decreased significantly between 1 and 15 wk. Distance out behind was positively correlated with tibia angle at all ages. The second study quantified linear and temporal kinematics of the walk in growing foals. Nine warmblood foals from the first study were filmed as they walked over a uniform concrete surface covered in 13mm thick rubber matting. Speed was controlled through the use of a uniform handler with a metronome. Trait means at ages 3, 11, 21 wk and post-weaning were compared. Length variables were standardized to percent of total stride length. Temporal variables were standardized to percent of stride duration. Stride length and duration increased significantly with age. Step lengths, stance duration and protraction and retraction durations did not change across ages. Over-stride decreased significantly with age, potentially due to increased back length in older foals. Linear distance between diagonal hooves during stance increased with age, and was negatively correlated to the decrease in over-stride. While older foals appeared to display a more regular, 4-beat walk rhythm, timing between lateral and diagonal footfalls remained significantly different at all ages. Both conformation and kinematics changed during growth. Characterizing conformational changes due to growth can allow a better understanding of how foal conformation and gait change during growth and may predict these traits in adults, thus allowing selection of top performance prospects at a younger age.

Key Words: Growth, conformation, development, equine biomechanics, foal, warmblood

ACKNOWLEDGEMENTS

I would like to sincerely thank the faculty, students, friends and family who have supported me during my time as a graduate student. First, I would like to thank the members of my committee for their support and encouragement. I thank them for taking the time to read this thesis and listen to my defense. Special thanks go to Dr. Rebecca Splan for accepting me as a graduate student and for her guidance and help with this project.

I would like to thank Shelby Clark for volunteering, and getting way more than she ever expected when she accepted the responsibility of leading all the horses, for every session from March 2006 to January 2007. I could not have done it without her, and I know that metronome still haunts her! Kathy Wilson and Katie Campbell both helped tremendously with my data collection. They were wonderful foal handlers and made the process as fun as possible. Thanks to all three girls for their support that summer and continued friendships. I would also like to thank the multitude of other undergraduate students who were involved in making this research possible.

Rebekah Cosden, Tracy Tomascik and Amanda Liles deserve huge thanks for being such wonderfully supportive friends and great office mates. I could not have done this without their encouragement and friendship. Tracy was available more than once, for a last minute hand with dots and videos! Their moral support was invaluable through-out this process. I hope that we remain friends long into the future. Sarah Parsley, Michelle Huntington, and Jenni Benson are amazing. They were always around to help me and provided the comic relief and friendships I needed to stay sane over the last 2 years.

My family has always supported me in every way possible, and their love and encouragement has allowed me to come this far. My sincerest thanks and love to my Mom and Dad for always believing in me, and always making sure I believed in myself. Finally, my most heart-felt thanks go to my boyfriend Shay Mariani, who moved 1200 miles from home to be with me and support my ambitions here. Shay stepped up to help with research when I needed extra hands, fed horses many late nights when I couldn’t get home, and helped me through two foaling seasons of many, many nights spent away from home. Words can not describe how much his love means to me. Without his encouragement, support and wonderful sense of humor I could not have done this.

ATTRIBUTION

Several professors aided in the writing and research behind the chapters of this thesis. A brief description of their background and their contributions are included here.

Dr. Rebecca K. Splan - Ph.D. (Department of Animal and Poultry Sciences, Virginia Tech). Dr. Splan is the primary Advisor and Committee Chair. Dr. Splan provided guidance and council during throughout this project. Dr. Splan helped design this project, assisted with data collection, analysis and composition of these chapters. Her background in gait and conformation analysis played an essential role in the development of this research.

Dr. John J. Dascanio - DVM. (Department of Large Animal Clinical Sciences, Virginia Tech). Dr. Dascanio utilized his clinical understanding of equine anatomy and physiology to guide the authors understanding of these topics. Dr. Dascanio contributed significantly to the discussion of the role of epiphyseal plates and their relation to the results of these studies.

Dr. W. Burt Staniar - PhD. (Department of Dairy and Animal Science, Penn State). Dr Staniar's background in equine nutrition and growth research contributed significantly to the linear growth research included in Chapter 2. Dr. Staniar's previous research also allowed for some comparison of growth rates in Warmblood and Thoroughbred foals.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER II

CHAPTER III

CHAPTER IV

LIST OF FIGURES

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER I

Introduction

As equestrian sports grow in international popularity, the demand for high quality equine athletes continues to rise. International trade of horses and genetic materials is on the rise. As a result, the sport horse industry is growing worldwide. Warmblood breeds dominate the top levels of show jumping, dressage and eventing. Selective warmblood breeding is yielding impressive results, with athleticism, gait and conformational quality steadily improving. Sales prices are reaching record highs and the number of warmblood horses being imported and exported is greater than ever (Eurodressage.com, 2006). Conformation and gait quality are closely linked with performance and sales prices and in turn, the economic impacts of this growing industry (Icken et al., 2007).

Breeding objectives for warmblood horses stress the importance of gait quality and conformational soundness. A 2004 survey of 18 European warmblood breed registries revealed that 89% of registries considered conformation an important aspect of their breeding objectives (Koenen et al., 2004). Gait quality was reported as a breeding objective by 74% of registries. When registries were asked to weight the relevance of breeding objective traits on a scale of 0-10, with 0 being “no relevance” and 10 being “extremely relevant”, gait quality received the second highest average weight (8.6 ± 1.9 s.d.) with conformation listed as a close third (8.4 ± 1.0 s.d.). Of all the weighted traits, conformation had the smallest variability, with relevance ranging from 7-10 and 15 of 18 responding registries scoring its relevance ≥8 (Koenen et al., 2004).

Conformation and gait quality are also closely related to perceived animal value, and are major determinants of economic value (Schwark et al., 1988; Preisinger et al., 1991). Analysis of Hanoverian auction data from 1994 to 2004 revealed relationships between recorded animal attributes and sale prices. Total estimated breeding value for dressage, scores for gait quality and body size, which were all related to conformation and gait, are all significantly positively correlated to sales price (Icken et al., 2007).

Increasing demand for high quality warmbloods has impacted the size and economic impact of the sporthorse market worldwide. The sales prices of 51 warmblood horses sold in Ankum, Germany at the 27th annual 2006 PSI Auction of Elite Sport Horses, one of the largest and most select European warmblood auction sales, totaled 10,087,000 Euro ($13,600,000). Top sellers went to Japan, the Ukraine and Great Britain (EuroDressage.com, 2006). At the 2006 Elite Foal and Broodmare Hanoverian Auction in Germany, a new price record was set when a colt sold for 103,000 Euro ($138,800). Fifty-six percent (131 horses) of the horses sold went to foreign buyers; 3% (7 horses) were exported to the United States (Hannoveraner Verband, 2006). The US equine industry has a $39 million direct impact on the national economy and the warmblood sector of this industry has been growing steadily over the last 30 years (American Horse Council, 2005).

Despite the importance of conformation and gait on animal value and performance, there is a paucity of knowledge regarding quantification and assessment of these traits. While the developing field of equine biomechanics and the technology that supports this research has allowed for quantitative analysis of gait characteristics to become an important resource, subjective evaluation remains the primary method of investigating conformation, and very little research has been conducted with foals.

Subjective evaluation is the traditional method of evaluating horses for athletic potential and is advantageous because of its ease relative to more scientific methods such as morphometric measurements. As with many breeds, warmbloods are most often subjectively evaluated for quality. Breed registry approval of both stallions and mares for breeding is primarily subjective. Warmblood foal quality is also often subjectively evaluated by breed registries at a young age to evaluate the quality of these offspring and scores often imply a prediction of adult athletic ability. These foal inspections most often occur pre-weaning, when growth is still incomplete. Despite their widespread use, we have little quantitative understanding of how warmblood conformation and gait changes during growth.

Quantification of changes in conformation and gait during growth is an important part of a more objective approach to evaluating young horses which will allow a more accurate understanding of how foal qualities predict adult performance and improve the ability to compare animals of different ages. When a clearer understanding of how to effectively evaluate young animals for adult capacity is established, the evaluation of young foals becomes a more useful tool for both breeders and those looking to select top quality animals at a young age. Establishing normal growth and conformation development patterns will also aid the development of healthier management practices.

Objectives

The objectives of this study are:

1. to quantify the linear growth patterns of specific body segments in warmblood foals from birth to 9 mo of age,
2. to quantify the angular conformation changes occurring during the first 9 mo of growth in warmblood foals, and
3. to investigate the changes in linear and temporal walk kinematics of warmbloods during the first 9 mo.

CHAPTER II

Review of Literature

Warmblood Breed Registry History and Current Practices

History of Warmblood Breed Registries. The European Warmblood registries began as government founded and managed stud farms in the eighteenth and nineteenth centuries. Horses were an important resource for travel, warfare and agriculture, and thus their production warranted national governance. In the early 1900's, the role of horses in society changed significantly. With increasing mechanization, horses lost their traditional roles and were instead primarily bred for leisure and sport. With this change in breeding goals, responsibility for the state stud books has increasingly been converted to private breeders (Wallin et al., 1995).

Internationally, equestrian sport popularity has been steadily increasing, especially over the last half century (van Weeren, 2001). These sports, primarily dressage show jumping and eventing, are now dominated by warmblood breeds (van Weeren, 2001; World Breeding Federation of Sport Horses, 2007). The international increase in warmblood popularity has also been mirrored in the United States in recent decades. Since the 1980's, the establishment of warmblood breed organizations similar to or in partnership with European regional breed registries has been on the rise in the United States. Currently the U.S. boasts more than 15 warmblood breed registries (Dressage World, 2007).

Warmblood Inspections. Warmblood breed registries host inspections of breeding stock and resultant progeny, where pedigree assessment and subjective evaluation and scoring of gait, conformation and overall impression are used to assess animal quality.

These in-hand evaluations have become the most predominant assessment method of young warmblood foals. Foal inspection scores serve as a less biased evaluation than those of financially and emotionally invested horse owners. Mare, foal and stallion inspections are the primary resource for registries to evaluate genetic progress and insure that individual breeders are meeting registry breeding goals. Scores received at these inspections are also an important source of information for breeders regarding mare, stallion and progeny phenotypic quality (Olsson et al., 2006). Undefined judge prerequisites, differences between scoring systems and the highly subjective nature of these scores must be considered when utilizing these values.

Scoring Systems. Just as breeding goals and focus vary among registries, so do the scoring systems used to evaluate horses. The point scale, traits evaluated and image of an ideal phenotype differ between organizations. These differences make it difficult to compare scores assigned by different organizations.

While some organizations evaluate and score foals, other registries only evaluate for general acceptable quality prior to registration and branding. Many registries also assign scores for vaguely defined traits such as “over-all development.” Pedigree evaluation criteria also differ between organizations. Differences in registry breeding objectives make differences in evaluation processes understandable, yet these differences also make it difficult to compare scores between registries and accurately understand how and if these scores indicate animal quality. Location effects, potentially including biases in favor of some host cites, may also make comparing scores given by the same evaluators at different inspection cites complicated.

Judge Prerequisites. The criteria for evaluator selection are largely undocumented or poorly defined by breed registries. Often judges are career breeders, trainers and/or veterinarians with many evaluators also certified judges in disciplines such as dressage or show jumping. Due to their experiences within the sport horse breeding industry or related competition arenas, these evaluators are considered experts in their field. Some, but not all, domestic registries expect evaluators to serve as "learner" judges for the registry before becoming a primary evaluator for the registry (Swedish Warmblood Association of North America, 2006; American Hanoverian Society, 2007). The lack of uniform, defined prerequisite requirements and lack of a centralized training program certainly contribute to the subjective nature and variability of inspection scores.

Evaluator Effect. While subjective evaluation of conformation is the traditional and still primarily used method of evaluating equine conformation, this method has distinct weaknesses. Subjective evaluation of conformation varies greatly between judges and is more repeatable for some traits than others (VanVleck and Albrectsen, 1965; Magnusson, 1985b). Grundler (1980) reported that repeatability, or the consistency of scores for one animal by a single judge, ranges from low (e.g., 0.31 for hoof-size) to high (e.g., 0.83 for croup length) (as cited by Magnusson, 1985b).

Attempts to improve the repeatability of subjective evaluation of Thoroughbred conformation scores through linear scoring yields mixed results. Linear scoring utilizes a numerical scale which describes traits from one biological extreme to another. This scoring method is used extensively in the Diary industry (Veerkamp, 2002). An example of this is body condition scores; a 1 is assigned to emaciated animals, while a 9 is assigned to extremely obese animals. Each number on these scales is clearly defined. Of

21 subjective, specifically defined linearly scored conformation traits, six traits were deemed unacceptably low in repeatability, as the coefficient of variation was greater than 10% (Mawdsley et al., 1996). These included head size, front and hind hoof pastern axis and camped out versus camped under evaluation of both the front and hind limbs (Mawdsley et al., 1996). Coefficient of variation for camped out versus camped under scores was as high as 20%; however this measurement was still included in the measurement protocol because of the authors' feelings that it was of practical significance to breeders (Mawdsley et al., 1996). Despite variability in scoring scales and traits investigated, linear scoring methods continue to be used to assess conformation traits in horses (Koenen et al., 1995; Dolvik and Klemetsdal, 1999).

Several distinct advantages to subjective evaluation warrant its continued use in both research and industry. This traditional method proves to be useful for estimating the genetic merit of young breeding stock in warmbloods, where performance records are not established until relatively late in their life (Holmstrom, 2001) Also, a single, knowledgeable evaluator is able to make conformational evaluation quickly. This system allows a large number of horses to be investigated in a shorter period of time than current quantitative methods allow (van Weeren and Crevier-Denoix, 2006). An experienced evaluator was able to score 21 conformation traits in approximately 10 min per horse (Mawdsley et al., 1996). Currently, objective quantitative evaluation of conformation and gait require a controlled laboratory environment that limit the number of horses which can practically be evaluated (van Weeren and Crevier-Denoix, 2006). Subjective evaluation may be as much an art as a science, however the information obtained through these methods is still valuable and should not be discredited. There is no indication that inspection scores given by subjective evaluators can or ever will be replaced by more objective methods.

Quantitative Evaluation of Conformation

Live Animal Measurements. The most straight-forward methods for quantifying linear conformation is to take measurements on the live animal using a flexible, non-stretch measuring tape or standard height stick with a level. These methods have been used extensively in equine growth research as accepted methods of quantifying linear conformation. Despite the common acceptance of these tools, their limitations should be understood.

Flexible measuring tape. When a trained individual uses clearly defined and easily found anatomical landmarks, a flexible measuring tape is effective and reliable. Morphometric measurements taken with a flexible measuring tape and replicated 10 times on 4 different horses by a single evaluator, resulted in standard error of the mean (SEM) ranging from ±0.38 (cm) for croup length, to ±0.02 (cm) for intramandibular width (Mawdsley et al., 1996). Wither height, back length from wither to highest point of croup, and neck circumference at the poll and larynx and at the withers and manubrium also yielded small SEM and were considered acceptably repeatable (Mawdsley et al., 1996).

Standard Height Stick. In a comparison of methods for measuring wither height, including a laser level and radiography, it was concluded that the measuring stick was an accurate, practical and satisfactory method (Hickman and Colles, 1984). However, stimuli that excite the horse such as exercise, trailer travel, being ridden, or receiving injections can increase wither height by an average of 0.5 to 2.2 cm. Heavy sedation with drugs such as xylazine decreases wither height by as much as 3.0 cm, mostly due to the change in stance to maintain balance (Hickman and Colles, 1984).

Photographic Measurements. In 1985 Magnusson developed and utilized a method of marking horses and measuring linear and angular conformation from still photographs (Magnusson, 1985b). Since this method was developed, angular conformation has almost exclusively been quantified through measurements taken from photos utilizing this system or a derivation of it. Many linear measurements such as that of scapula, humerus, pelvis and femur lengths are easier to measure photographically. Advances in computer technology have allowed investigation into potential error associated with photographic measurement methods. This system has become common in quantitative conformation research, but it is important to control known sources of error.

*Magnusson's Method****.*** Twenty-five anatomical points were chosen for paper marker placement on the live animal (Figure 1). Points were chosen to be easily palpable and not heavily influenced by muscle, fat or hair. They reasonably represented the end of bones and the center of joints, and the lines between these points coincided with lines and axis used in subjective horse evaluation (Magnusson, 1985a). Horses stood in a standardized, square position, and a measuring stick was included in each photo for scaling. Film was then developed to slides, and linear and angular measurements were taken from projected images (Magnusson, 1985a).

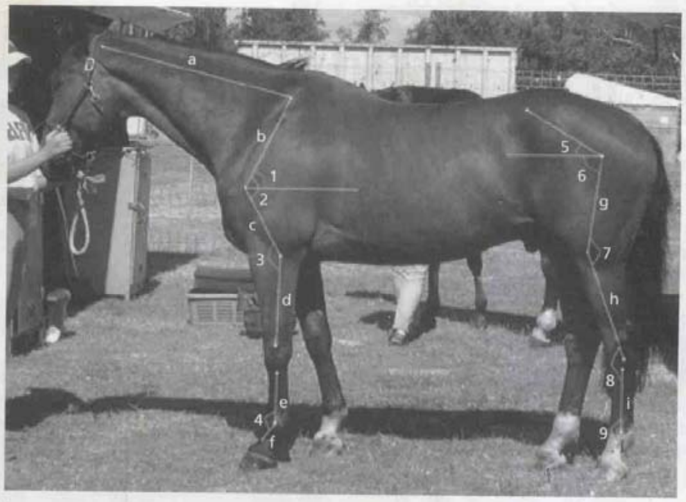


Fig. 11.2 **Length measurements** **a:** Neck; **b:** shoulder; **c:** humerus; **d:** radius; **e:** fore cannon; **f:** fore pastern; **g:** femur; **h:** tibia; **i:** hind cannon; **j:** hind pastern.
Angle measurements **1:** Shoulder inclination; **2:** shoulder joint; **3:** elbow joint; **4:** fore fetlock joint; **5:** pelvis inclination; **6:** femur inclination; **7:** stifle joint; **8:** hock joint; **9:** hind fetlock joint.

Figure 1. Example of a horse marked and measured utilizing Magnusson's photographic method (taken from Holmstrom, 2001).

Distortion Error. Translating the 3-dimensional (3D) animal to a 2-dimensional (2D) image and planar differences between markers create measurement error. Increasing the lens's focal length from 40mm to 200mm significantly reduces this distortion (Magnusson, 1985a). When compared to measurements taken from a 3D system, 2D measurement error averaged 2 cm with a maximum error of 5 cm for the scapula length (Weller et al., 2006a). Corrections for "fish-eye" distortion caused by video and camera lens attributes range from 0 cm at the center of the screen to 2 cm at image edges (Hunt et al., 1999).

Camera Placement. Camera placement is an important concern when utilizing photographs to measure conformation. The camera should be placed at a height as close to that of the center of horse's thorax as possible. Overly high camera placement causes significant overestimation of horizontal and vertical linear measurements taken from the upper half of the frame (Hunt et al., 1999). Measurements from the lower half of the frame or that span the entire image are either underestimated or unaffected. Low camera placement has a much less severe effect on measurement error, but does cause some overestimating of measurements taken high in the image frame (Hunt et al., 1999).

Marker Application. Error due to incorrect marker placement is also a concern when utilizing photographic measurement techniques. Coefficients of variation for linear measurements taken by a 3D camera system range from 0.62% for wither height to 19.25% for carpus length when comparing the marker application of three trained individuals (Weller et al., 2006a). Mean absolute value differences in angular measurements revealed the greatest differences in angles measured using the tuber sacrale, humerus and stifle markers (Weller et al., 2006a).

Utilizing a single practiced individual to mark all animals in a study is often done to control error associated with differences between applicators. From measurements taken after multiple marker applications by a single individual, mean differences greater than 2 cm were reported for neck, trunk length, croup length and tibia (Weller et al., 2006a). Length measurements distal to the carpus and tarsus averaged less than 1cm difference between marker applications. Angular absolute value differences between markers average 3.2° (Weller et al., 2006a). Variation was greatest in measurements utilizing the marker over the greater trochanter of the femur due to the increased muscle covering which makes exact placement more difficult (Weller et al., 2006a).

Animal Stance. As with measurement taken from live animals, a uniform stance for photographs is important for accuracy and repeatability. Changes in limb placement and weight distribution can significantly influence angular conformation measurements.

Early researchers in this field often noted the importance of utilizing a standardized animal stance when evaluating equine conformation through photographs or human observation (Holmstrom et al., 1990; Mawdsley et al., 1996). The changes in angular conformation are easily observable. However, little published research is available quantifying the effects of stance on angular conformation. When one horse was repositioned 25 times into a standardized position after a single marker application variability between measurements was highest for neck and body lengths and front and hind hoof-pastern axis and fetlock angles (Weller et al., 2006a). Therefore while using a standard position helps reduce error due to stance, these measurements remain the most highly variable.

Linear Conformation Changes During Growth

Understanding normal equine growth rates is important for healthy management practices and for further investigation into developmental orthopedic diseases such as osteochondrosis (Pagan et al., 1996; Finkler-Schade et al., 1999). Some linear conformation traits have also been associated with performance and athletic ability (Holmstrom et al., 1990; Holmstrom and Philipsson, 1993). Growth rates have been thoroughly investigated in racing breeds, particularly the Thoroughbred. Season, weaning, foal sex and dam parity have an effect on growth rates (Poolanderson et al., 1994; Kavazis and Ott, 2003; Rogers et al., 2004). Warmblood growth, similar to other breeds, is the most rapid during the first month of life, begins to slow and then a second growth spurt occurs during the twelfth month of life (Finkler-Schade et al., 1999; Staniar et al., 2004b). Little work has been done to quantify normal growth of individual body segments in warmblood foal populations (Splan et al., 2007). Therefore, due to the paucity of warmblood data the following sections outline growth rates of several commonly investigated physical traits in multiple equine breeds.

Body Weight. While body weight (BW) is not typically considered when evaluating conformation, it is easily quantified and often included when investigating growth. Abnormally high weight during growth has been correlated to the incidence of osteopathic lesions in warmblood horses (van Weeren et al., 1999; Vervuert et al., 2005). Thus, the quantification of normal weight gain patterns is of concern in the healthy management of growing young warmbloods.

Reported mean warmblood birth weights range from 53.3 to 57.3 kg (Vervuert et al., 2005; Donabedian et al., 2006). In a small population of Lipizzan horses, which are reasonably similar to warmblood breeds, birth weights average 47.9 kg. Lipizzan foals average daily gains are reported highest until 9 mo of age and slowly leveled off by 27 mo of age (Lovsin et al., 2001). Somewhat surprisingly, mean birth weights in Thoroughbreds are similar to warmblood values (Hintz et al., 1979; Kavazis and Ott, 2003). However by 181 to 210 d of age (7 mo), mean warmblood weights are reported to reach 263 kg (Vervuert et al., 2005), while several authors report Thoroughbred mean values at this age between 237 and 245 kg (Hintz et al., 1979; Kavazis and Ott, 2003). Other studies in Thoroughbreds report mean values at 7 mo of age between 260 and 282 kg (Thompson, 1995; Staniar et al., 2004a); exceeding reported values in warmbloods. However, environmental variability (e.g., housing, location, time of year and nutrition) among studies may certainly account for these differences. Similarities between birth weights and differences between mean weights at older ages and adulthood imply differences in growth rates between breeds. Further investigation of weight changes during growth are warranted in warmblood populations for a more complete understanding of healthy daily weight gain patterns.

Wither and Hip Height. Due to the lack of growth research in warmbloods, wither (WH) and hip height (HH) growth patterns have not been clearly defined. However, many researchers investigating factors other than growth have published mean wither height values from warmblood herds at various ages.

Mean WH at birth in a group of 39 French warmbloods was reported as 102.1 cm (Donabedian et al., 2006). Mean WH at 4 mo of age in two different groups of Dutch warmbloods were 131 cm and 129.5 cm (Back et al., 1995; van Heel et al., 2006). By 6 mo, Dutch warmbloods had grown to a WH of 140 cm, while French warmbloods' WH at this age was only 134 cm (Bobbert et al., 2005; Donabedian et al., 2006). Van Heel et al. (2006) reported WH to be 154.2 cm in Dutch warmbloods at 14 mo. Two year old Dutch warmbloods were reported to be 161.5 cm tall at the withers (Back et al., 1996). Reported adult (4-20 y of age) Lipizzan, Swedish and Dutch warmblood mean WH ranged from 153 to 166.0 cm (Holmstrom et al., 1990; Lovsin et al., 2001; Bobbert et al., 2005).

Average increases in WH from birth to 6 mo of age in French warmbloods was 5.1 cm/mo (Donabedian et al., 2006). Research in Lippizan horses report average gains in WH as highest from birth to 9 mo, 3cm/mo from birth until 12 mo and 0.7 cm/mo from 12 to 27 mo of age (Lovsin et al., 2001). Wither height growth in warmblood horses raised in North America slowed by 540 d (18 mo) of age (Splan et al., 2007), but later ages were not investigated.

Hip height (HH) values during growth are less frequently reported. Thoroughbred research has shown HH to follow a similar pattern to WH (Thompson, 1995; Kavazis and Ott, 2003; Anderson and McIlwraith, 2004). Hip height remains 2-3 cm greater than WH in Thoroughbreds until 20 mo of age (Thompson, 1995). However, at 2 years of age WH and HH are similar, and at 3 years of age, mean WH exceeds HH in Thoroughbreds (Anderson and McIlwraith, 2004). In Swedish Standardbred Trotter colts, HH exceeds WH by 2-4 cm from 6.5 to 25.5 mo of age (Magnusson, 1985b). In adult Swedish warmbloods, WH exceeds HH by an average of 2.5 cm (Holmstrom et al., 1990). An "up-hill" (WH > HH) build is considered desirable in most breeds, as it is believed to be a more athletic frame (Hedge et al., 2004). "Down-hill" (HH > WH) conformation is commonly recognized as a fault that young horses will outgrow (Hedge et al., 2004). Investigation into HH growth patterns are important in understanding at what age an up-hill build should be expected. These values give a general outline of normal parameters for WH in warmbloods of various ages and HH trends in other breeds. However, more research involving repeated measures on growing animals is needed before an accurate understanding of normal WH and HH growth rates for warmbloods can be established.

Body Length. Significant body length (BL) growth occurred between birth, 30, 60, 90, 180, 360 and 540 d of age in North American warmbloods (Splan et al., 2007). However, body length growth slowed, and no significant differences were seen between mean values at 540 and 720 d of age. The small number of animals measured at 720 d may have influenced these results (Splan et al., 2007). In 10 Swedish Standardbred Trotters, a racing breed more similar to Thoroughbreds than warmbloods, BL increased from 123.9 cm at 6.5 mo of age to 152.1 cm at 25.5 mo of age (Magnusson, 1985b).

From 6.5 to 16.5 mo of age, average BL gains were approximately 2 cm/mo. However, growth slowed to 1.1 cm/mo between 16.5 and 19.5 mo of age and 0.8 cm/mo between 19.5 and 25.5 mo of age (Magnusson, 1985b).

Relationships between BL, WH and HH are an important part of conformational balance, or the symmetry and proportionality of a horse's build (Hedge et al., 2004). Standardbred BL increased a total of 23% from 6.5 to 25.5 mo of age, compared to only an 18% increase in WH (Magnusson, 1985b). Average adult Swedish warmbloods have WH 2-3 cm greater than BL (Holmstrom et al., 1990). However, adult Lipizzan horses only average WH 0.5 cm greater than BL (Lovsin et al., 2001). Lipizzaner horses are often considered a more compact breed; perhaps a reflection on the different relationship between WH and BL in these horses.

Girth. Many studies investigating growth include a heart girth circumference measurement. Heart girth circumference (HG) has been proven to be an accurate measurement for estimating body weight (Milner and Hewitt, 1969; Jones et al., 1989). In growing Thoroughbreds, HG positively correlated with weight at birth, 4, 6, 12 and 15 mo of age (Kavazis and Ott, 2003). Accurate weight estimation has been accomplished in growing Thoroughbred foals utilizing HG and other body measurements (Staniar et al., 2004a).

Lipizzan foals at birth averaged 94 cm HG, compared to means between 82 and 89 cm in Thoroughbred foals from birth to 14 d of age (Green, 1969; Lovsin et al., 2001; Kavazis and Ott, 2003). In Lippizan horses, growth dynamics of HG were similar to WH, with fastest growth occurring within the first 9 mo (Lovsin et al., 2001). Swedish Standardbred Trotters inceased HG by 28% between 6.5 and 25.5 mo of age (Magnusson, 1985b). Warmblood HG is reported to continue significant growth through 24 mo of age (Splan et al., 2007). Heart girth growth in warmblood foals requires further definition.

A disadvantage to this measurement is that it can not be quantified using 2-D photographic methods. The height of the ribcage can be measured photographically, but this fails to account for the widening of the ribcage which occurs during growth.

Forelimb. Equine growth research has shown that the long bones in the forelimb grow at different rates (Magnusson, 1985b; Anderson and McIlwraith, 2004). Tables 1 - 3 display forelimb growth data from three different breeds. All data presented in these tables were taken from photographs or video.

First phalanx and third metacarpal growth is reported to slow significantly by 90 - 180 d of age in warmbloods and racing breeds (Hintz et al., 1979; Fretz et al., 1984; Magnusson, 1985b; Thompson, 1995; Splan et al., 2007). There is no significant difference between third metacarpal length at 4 and 26 mo of age in Dutch warmbloods (Table 1). However, metacarpal and carpal joint circumferences are reported to increase significantly until 1 yr of age in North American warmbloods (Splan et al., 2007).

Radius, humerus and scapula growth continues to later ages. Magnusson (1985b) reported that radius and humerus lengths increased 19% and 27% respectively from 6.5 to 26.5 mo of age in Standardbred Trotters (Table 2). In comparison, combined carpus and cannon length only increased 1% during this time (Magnusson, 1985b). Significant differences between radius, humerus and scapula length in Thoroughbreds are seen between birth, 1 and 2 yr; however by 3 yr growth has slowed (Table 3). Radius growth in warmbloods is reported to slow significantly after 360 d (12 mo) of age (Splan et al., 2007). Back et al (1995) reported that humerus growth (54% increase) contributed more to increased wither height than scapula growth (42% increase) in Dutch warmblood foals between 4 and 24 mo. However, scapula length increased the most (30%) of all bones in the forelimb of Standardbreds from 6.5 to 25.5 mo (Magnusson, 1985b).

Front Limb Conformational Variables by Age
DUTCH WARMBLOODS

Trait (cm)	4 mo	26 mo
Scapula	25.7^a	36.5^b
Humerus	14.1^a	21.7^b
Radius	32.3^a	40.7^b
Cannon	30.2	32.2

Values are mean
Superscripts indicate significant differences ($P < 0.05$)
(Back et al., 1995)

Table 1. Front limb linear conformation variables of Dutch warmbloods at 4 and 26 mo of age.

Front Limb Conformational Variables by Age
STANDARDBREDS

Trait (cm)	6.5 mo	10 mo	13 mo	16.5 mo	19.5 mo	22.5 mo	25.5 mo
Scapula	28.2 (0.6)	30.0 (0.5)	31.4 (0.5)	32.9 (0.4)	34.5 (0.6)	35.8 (0.4)	36.8 (0.4)
Humerus	23.8 (0.4)	26.1 (0.5)	27.1 (0.4)	28.3 (0.4)	28.5 (0.4)	29.2 (0.3)	30.3 (0.2)
Radius	29.3 (0.5)	30.9 (0.3)	32.6 (0.3)	31.6 (0.2)	33.3 (0.3)	33.8 (0.3)	34.8 (0.3)
Carpus + Cannon	31.1 (0.3)	31.6 (0.1)	32.0 (0.3)	31.6 (0.2)	31.7 (0.2)	31.4 (0.2)	31.6 (0.2)
Pastern	10.0 (0.2)	10.5 (0.2)	9.6 (0.2)	10.0 (0.2)	8.9 (0.2)	9.2 (0.3)	9.0 (0.1)

Values are mean (SEM)
(Magnusson, 1985b)

Table 2. Front limb linear conformation variables of Standardbred colts from 6.5 to 22.5 mo of age. Significant differences between age groups were not reported.

Front Limb Conformational Variables by Age
THOROUGHBREDS

Trait (cm)	0 yr (weanling)	1 yr	2 yrs	3 yrs
Scapula	34.9 (0.5)	43.3 (0.4)^{a}	47.7 (0.4)^{b}	48.0 (0.4)
Humerus	20.6 (0.3)^{a}	26.2 (0.3)^{b}	29.9 (0.3)^{c}	29.9 (0.2)
Radius	37.3 (0.5)^{a}	42.7 (0.4)^{a}	44.3 (0.4)^{c}	43.4 (0.4)
Cannon	28.9 (0.3)	29.7 (0.2)	30.3 (0.3)	30.3 (0.2)
Pastern	13.1 (0.2)	13.3 (0.1)^{a}	13.9 (0.1)^{b}	13.8 (0.1)

Values are LSMean (SEM)
Superscripts indicate significant differences ($P < 0.05$)

(Anderson and McIlwraith, 2004)

Table 3. Front limb linear conformational variables of Thoroughbreds from weanlings to 3 yr of age.

Hindlimb. Growth in the hindlimb is reported to be similar to that of the forelimb with distal bone growth slowing at an earlier age than those located proximally (Magnusson, 1985b; Anderson and McIllwraith, 2004). Third metatarsal growth has been shown to slow significantly in warmbloods by 3 mo of age (Splan et al., 2007). Dutch warmblood foals' mean metatarsal length did not change between 4 and 26 mo of age (Back et al., 1995). In Thoroughbred foals, metatarsal length was reported to increase an average of 0.28 cm/mo between birth and 14 mo of age (Staniar et al., 2001). Anderson and McIlwraith (2004) reported no significant difference between metatarsal length in weanling versus yearling Thoroughbreds. However, significant growth was reported between 1 and 2 yr, but not between 2 and 3 yr.

A limited number of studies have measured tibia, femur and pelvis lengths. Pelvis and femur lengths are particularly difficult to measure from the live animal. Back et al. (1995) reported large amounts of growth in the tibia, femur and pelvis from 4 to 26 mo of age in Dutch warmblood foals. In these foals, tibia length increased 26%, femur length increased 40% and pelvis length increased by 71%. However, in Standardbred colts the tibia, femur and pelvis lengths were all reported to increase by only 25% between 6.5 and 26.5 mo of age (Magnusson, 1985b).

Epiphyseal Plate Closure. Bone growth occurs at the epiphyseal plates. These "growth plates" are cartilidge plates within the ends of long bones. These plates play a primary role in longitudinal bone growth and bone modeling (Karaharju, 1976; Fretz, 1984). During adolescence, the cartilage in growth plates is slowly replaced by bone and when this ossification occurs, no further longitudinal bone growth can occur (Fretz, 1984).

There are multiple methods for investigating the closure time of epiphyseal plates. The specifics of these methods are beyond the scope of this review, however the method used does affect the identified closure time of epiphyseal plates (Fretz, 1984). When investigating gross specimens, the epiphyseal plate at the distal end of the radius closes between 3 and 3.5 yr (Rooney, 1963). However utilizing radiography, closure time is estimated to be around 2 yr (Myers and Emerson, 1966; Fretz, 1984). At the distal end of the metacarpal bone, plate closure time estimated from cadavers ranges from 10 to 18 mo (Tohara, 1950; Rooney, 1963) and from radiographs ranges from 7 to 18 mo (Myers and Emerson, 1966; Fretz 1984). Radiographic closure time of distal metatarsal growth plates are reported to range from 9 to 12.5 mo (Fretz, 1984). The growth plates in the proximal end of the first phalanx are estimated to close between 9 and 15 mo when investigating gross specimens (Tahara, 1950; Rooney, 1963). However, utilizing radiographs, growth plate closure in the first phalanx (both front and hind limb) is reported to occur between 6 and 11 mo (Myers and Emerson, 1966; Fretz, 1984). Clearly the methodology can have an effect on estimated closure times. It is also possible that differences between investigated horse breeds, genetics, nutrition, or housing conditions contribute to the differences in reported closure times.

Research has focused on identifying the closure time of plates located in the equine limb, primarily the distal limb. This is in part due to the interest in understanding how to treat lower limb angular deformities in young foals. Also, increased muscle coverage over proximal limb bones and the spine make imaging more complicated (Morgan, 1991). However, from the research outlined above, it is clear that epiphyseal plate closure times supports that growth in the distal limbs finishes at an earlier age than in proximal limb.

Angular Conformation Changes During Growth

Angular conformation is associated with gait quality, performance and athletic potential (Holmstrom et al., 1990; Back et al., 1994a; 1996). The concept that angular conformation is changing during early growth is prevalent within the sport horse breeding industry and has led to several anecdotally supported beliefs on the best timing for evaluating young stock. Knowledge of an “ideal window” for evaluation is desirable as foal inspections occur on a calendar date basis and received scores are important for the marketing of young sales horses. Early detection of superior equine athletes saves economic losses due to the training and care of animals which do not have the inherent talent to become successful in their discipline (Back et al., 1995). However, there is limited previous research quantifying angular conformation. The following sections outline the published research investigating changes in angular conformation during growth.

Forelimb. When evaluating angular conformation in the forelimb, a primary focus is often the angle of the scapula. A long, laid back scapula is preferred as it is commonly believed to produce a more favorable gait pattern. In Thoroughbreds and Standardbreds, scapula angle has been shown to increase, or become more upright, during growth (Magnusson, 1985b; Anderson and McIlwraith, 2004). Many studies have investigated changes in shoulder (scapulohumural) joint angle. Dutch warmbloods, Standardbreds and Thoroughbreds had an approximately 6% more extended shoulder angle as 2 yr olds then as 4-6 mo old foals (Magnusson, 1985b; Back et al., 1995; Anderson and McIlwraith, 2004). The elbow joint (humerus and radius) appeared 3% more extended at older ages (Magnusson, 1985b; Back et al., 1995). Front fetlock angles also become more extended during growth (Magnusson, 1985b; Anderson and McIlwraith, 2004).

In 17 grade Quarter Horse and Thoroughbred foals 6 to 8 mo of age, correlations among angular and linear measurements were reported. Shoulder angle and elbow angle were significantly positively correlated (r = 0.75). These angles were also significantly negatively correlated to radius (r = -0.67 and -0.57 respectively) and humerus length (r = -0.60 and -0.57 respectively) (Leach and Cymbaluk, 1986). Shoulder angle also negatively correlated (r=-0.47) to front cannon length (Leach and Cymbaluk, 1986). However it is unclear how these correlations may change as the animal ages.

Forelimb conformation is also often evaluated from the front of the horse for medial and lateral deviations of the limb to be considered. Subjective and quantitative methods of measuring rotational deviations of the carpus, and degree of “toed-in” or “toed-out” have been developed. Results in Thoroughbreds (Anderson and McIlwraith, 2004) and warmbloods (Splan et al., 2007) report a trend from toed-out younger horses to a straighter stance in older animals. A significant negative correlation between chest width and degree of foot deviation is reported in growing warmbloods from birth to 2 yr of age (Splan et al., 2007).

Hindlimb. Despite the athletic importance of the angular conformation of the hindlimb, there has been virtually no investigation of how these angles change during growth (Ross, 2003). Magnusson (1985b) reports very small changes in pelvic inclination during growth, but no trend or significant differences were established. In both Standardbreds (Magnusson, 1985b) and Dutch warmbloods (Back et al., 1995) the hip and stifle joints were more extended in 2 yr old horses than foals. No significant differences were reported for hock angle between ages.

Relationships between angular and linear conformation traits in grade foals between 6 and 8 mo of age have been reported. Hip joint angle significantly correlated to both stifle ($r = 0.50$) and hind fetlock angle ($r = 0.49$). Hip ($r = -0.47$) and stifle ($r = -0.53$) angles were also negatively correlated to tibia length (Leach and Cymbaluk, 1986). Further investigation of how these relationships change with age are necessary for understanding the effects of growth on conformation.

Gait Analysis

The ability to more successfully predict and enhance the performance potential of equine athletes has been approached from many sides. Nutrition, muscle physiology, cardiology and exercise physiology are all popular areas of research in an attempt to better understand the needs of equine athletes (Dalin and Jeffcott, 1985). However, another very important factor in the performance of equine athletes is the locomotor system. The objective of biomechanics research is to gain a more thorough understanding of gait pattern and locomotion. The interest in understanding equine locomotion and how it influences the athletic ability of the horse has fueled the developing field of equine biomechanics research (Dalin and Jeffcott, 1985; Barrey, 1999; Clayton, 1999).

History. The famous Greek philosopher, Aristotle (384-322 BC), is responsible for the first documented study of animal locomotion. Aristotle accurately described the motion pattern of quadrupedal animals at the slower gaits (as cited by van Weeren, 2001). Since this early interest, scientists and veterinarians have slowly developed the study of equine locomotion. The first modern work focusing entirely on equine gait was published in 1779 by French scientists who were members of the new veterinary center in Paris (van Weeren, 2001). In Switzerland between 1821 and 1824, Conrad von Hochstatter published several books discussing the mechanisms of equine gait and the consequences of poor conformation (as cited by van Weeren, 2001).

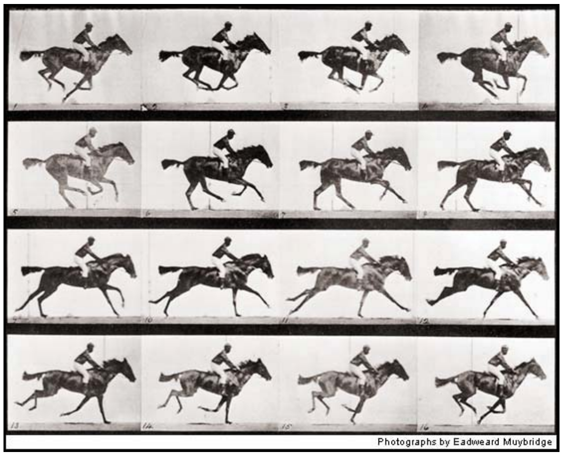


Figure 2. Galloping horse photograph series
(Muybridge, 1899)

However, in 1877 the study of equine gait was revolutionized by the work of photographer Eadweard Muybridge. Muybridge used 24 cameras and a series of thin strings which when crossed by a moving animal triggered photographic exposure (Fig. 2). Impressively, Muybridge had also managed to speed camera exposure to 1/6000 of a second, an amazing feat allowing high quality photos of moving animals (Muybridge, 1899; van Weeren, 2001). Muybridge's work was the precursor to modern cinema and videography.

Around the same time in France, Etienne Marey, a physiologist, developed several mechanical devices which allowed him to investigate the movement of horses and other species. Basic pressure sensors attached to the bottom of the hooves and around distal limbs, connected to recording devices allowed Marey to calculate limb sequences and stance and swing durations. The use of a series of open and closed bars to describe limb placement is attributed to Marey, and is still commonly used today. Marey was also one of the first to write that the hindlimbs are the source of propulsion, while the forelimbs provide support (as cited by van Weeren, 2001).

Modern Research. With the rise in popularity of horses for leisure and sport, a renewed interest in equine biomechanics emerged. The modern wave of equine biomechanics research started with the work of Dr. Stig Drevemo in Sweden and Dr. James Rooney in the United States in the 1970's. These researchers began utilizing high speed cinematography to study equine gait. However, digitizing still had to be done by hand and cumbersome mainframe computers were used for computations, making the work tedious (Clayton, 1999).

Kinetics. The objective of kinetic biomechanics research is to investigate the forces responsible for motion. Several areas of kinetic research include joint force, torque, work, angular accelerations and ground reaction forces (Winter, 1990). Force plates, which measure longitudinal, transverse and vertical ground reaction forces play a primary role in investigating forces acting on the distal limb during locomotion (Dalin and Jeffcott, 1985; Barrey, 1999). One problem with force plates is the limb missing contact with the plate during locomotion, or striking an edge where measurement is less accurate (Dalin and Jeffcott, 1985; Leach, 1987; Clayton and Schamhardt, 2001). However, as force plates have become larger and often imbedded under high speed equine treadmills, these problems have been reduced.

The concept of a device attached to the foot to measure ground reaction force began with Marey's work in the 1870's. Modern versions of this device have been utilized with mixed success by researchers since 1970 (Clayton and Schamhardt, 2001). However, the added weight to the distal limb can influence gait pattern and be dangerous at high speeds and there is concern over the accuracy of measurements obtained from these devices (Roepstorff and Drevemo, 1993; Dalin, 1994; Barrey, 1999; Clayton and Schamhardt, 2001).

Strain gauges and accelerometers have also developed over the last 30 years and are important in kinetic research. Strain gauges have been developed and utilized to measure forces acting on the bone and ligaments in both *in vivo* and *in vitro* studies (Barrey, 1999; Clayton and Schamhardt, 2001). Accelerometers attached to body segments can measure and record the acceleration of the segment. These are most often attached to the hoof wall in equine research to detect ground contact (Clayton and

Schamhardt, 2001). Accelerometers have also been used on the torso to examine left/right asymmetries in the trunk and diagnose subtle unsoundness (Barrey and Desbrosse, 1996).

Kinematics. The objective of kinematic research is to examine the spatial and temporal characteristics of movement without reference to the forces causing the movement (Winter, 1990). The development of high speed digital video has revolutionized kinematic analysis. Early video analysis was cumbersome and required an in-depth digitization process before any results could be analyzed (Dalin and Jeffcott, 1985). Huge improvements in image quality, recording speeds, and software have greatly simplified this process (Clayton and Schamhardt, 2001). Several software packages have been developed for equine biomechanics research (Clayton and Schamhardt, 2001). These programs can automatically track user defined skin markers, filter and smooth signals allowing real-time data capture and analysis (Clayton and Schamhardt, 2001).

Basic skin markers are a passive marker system; meaning that no signal is directly received from each marker. Visual tracking from video of horses marked with passive markers allow kinematic data to be collected. However, active marker systems have been developed. Most commonly a modified Cartesian Optoelectronic Dynamic Anthropometer (CODA-3) system is used. The modified CODA-3 system can track many markers simultaneously in 3D, and data are available almost instantly (van Weeren et al., 1990b; Barrey, 1999; Clayton and Schamhardt, 2001). This system does not require calibration prior to each use as the coordinate system is calculated relative to the frame of the machine (Clayton and Schamhardt, 2001).

High speed equine treadmills also revolutionized the study of equine gait. Measurements can be recorded at high speed gaits with a stationary camera. Variables from multiple strides can easily be collected during a single session. Early research validated the use of treadmills when gait patterns measured over track conditions were repeatable on the treadmill (Fredricson et al., 1983). Other researchers have validated the use of the treadmill through repeatability tests of measured kinematic variables (Faber et al., 2002).

Considerations for Gait Analysis

The research presented in this thesis focuses on kinematic analysis of gait; therefore this review will focus on the considerations of kinematic gait analysis technologies. The following sections review several important areas of concern when investigating equine gait pattern.

Marker Placement. As with quantitative analysis of conformation, there is concern over the marker placement accuracy in kinematic gait analysis. Landmarks used in kinematic research are similar to those used in conformation research (Fig 3). Measurements of range of motion, flexion and extension rely on the accurate placement of markers over appropriate anatomical landmarks.

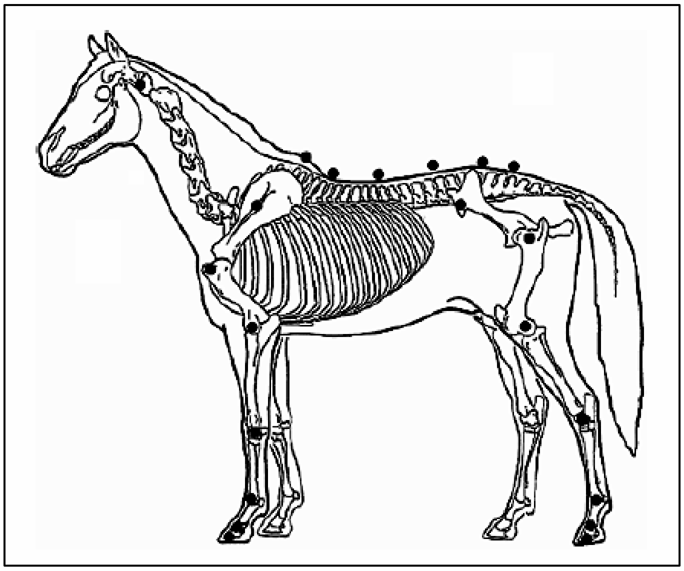


Figure 3. Anatomical markers commonly utilized in kinematic research

(from Clayton and Schamhardt, 2001)

Markers used for conformation analysis identify the end of long bones, while the markers for kinematic analysis mark the estimated center of joint rotation (Magnusson, 1985b; Clayton and Schamhardt, 2001). Despite this, many of the markers are the same. The markers in the proximal hindlimb, over the tuber sacrale, humerus and stifle, are reported to have the lowest repeatability (Weller et al., 2006a). It is important that a single trained evaluator marks all horses in a study.

Skin Displacement. Skin markers are the common method of marking bones and joints for kinematic gait analysis. However, skin slides over joint surfaces during motion. This skin displacement creates error in kinematic measurements, because the marker location does not accurately display joint location through-out movement (Clayton and Schamhardt, 2001).

The error due to skin displacement has been recognized by equine biomechanics researchers since 1910. Willem Kruger, in 1937, addressed this problem by oiling the horses' skin and using indirect lighting to visualize the bones (van Weeren, 2001). Modern researchers have been able to quantify skin displacement. In 1986, van Weeren et al. investigated skin displacement utilizing subcutaneous light emitting diodes (LEDs) and skin markers. Due to the method of LED implantation, this method is limited to the distal limb. At the walk, skin displacement in fetlock is relatively small, while skin movement at the tarsal and carpal joints reached up to 2 cm (van Weeren et al., 1988).

Skin displacement of proximal limb joints is investigated utilizing pins surgically implanted into the bone (van Weeren et al., 1990). Vertical and horizontal displacement of most sites ranges from 1 to 5 cm, however in the proximal part of the femur, displacements reached as high as 15 cm (van Weeren et al., 1990).

Correction algorithms for skin displacement are available, but these are speed-dependent and only useful in animals of similar conformation (van Weeren et al., 1992; Lanovaz et al., 2004; Sha et al., 2004). The associated cost and concern that surgery and pins distort normal gait pattern make implanted markers a sub-optimal method for kinematic research. Correction algorithms for skin displacement allow for sufficient accuracy when utilizing skin markers (Clayton and Schamhardt, 2001).

Speed Dependency. Gait speed has a significant effect on linear, temporal and angular kinematics of horses. Stride and step lengths are positively correlated to speed in horses on a track and a treadmill at walk, trot and canter (Leach and Cymbaluk, 1986; Leach and Drevemo, 1991; Galisteo et al., 1998; Hoyt et al., 2000). Stride duration shortens with increased speed, which is primarily due to a shortened stance phase at higher speeds (Galisteo et al., 1998; Hoyt et al., 2002). Angular kinematics also vary with speed. Angular range of motion within the proximal limb joints, with the exception of the stifle joint, increases with speed (Galisteo et al., 1998; Hoyt et al., 2002). The range of motion in the entire hindlimb increased by 27% when speed increased from 2 m/s to 4 m/s (Hoyt et al., 2002). Speed also has a significant effect on motion pattern consistency. When horses are run at speeds above or below their energetically optimum speed, motion patterns become inconsistent (Peham et al., 1998). Inconsistent motion patterns make kinematic traits from repeated strides highly variable. Controlling speed through the use of a treadmill, uniform handler or metronome is vital during the study of equine kinematics.

Calibration and Filtering. When quantifying kinematics during gait from video, calibrations are necessary. A measured length must be included in the visual frame and defined within the software so that distances can be accurately measured from the video (Clayton and Schamhardt, 2001). While the modified CODA-3 system does not require this calibration, many other research environments require a defined frame of reference for both linear and angular measurements. While software is capable of tracking the markers, the user must define the coordinate system for angular variables to be uniform and comparable (Clayton and Schamhardt, 2001).

Raw video data contains electrical noise, or unwanted signal characteristics due to random fluctuations of the electric current, which must be filtered out (Winter, 1990). Often this is high frequency noise which can be easily removed using a high frequency filter. High frequency signals rapidly increase in amplitude when differentiated; therefore having severe effects on velocity and acceleration derivatives (Winter, 1990). Many of the high tech biomechanics software packages have built in high frequency filters which can be utilized to smooth data (Clayton and Schamhardt, 2001). However, programming code can also be written in computing environments such as MATLAB® to filter noise from kinematic data (MathWorks, 1994-2007).

Linear and Temporal Kinematics of the Walk

By understanding normal gait pattern, the effects of different footing, lameness, being ridden and growth can be investigated. In 1983 Leach and Crawford discussed guidelines for the future of equine locomotive research. These authors recognized that the characterization of normal gait patterns was one of the first and a very important step in understanding equine locomotion. Researchers are still working to quantify normal gait pattern. While the most investigated gait remains the trot, work has been done in other gaits and these sections outline previous research quantifying kinematics of the walk.

Basics of the Walk. The walk is a symmetrical, four-beat gait with no period of suspension and large overlap times between limb stance phases (Hildebrand, 1965). Many "gaited" breeds display variations of the walk, which are also 4-beat gaits. This review focuses on the non-gaited, pure basic walk. Basic temporal characteristics of the walk are summarized in Table 4.

Age	Footfall Sequence	Type of Symmetry	Speed (m/s)	Stride Length (m)	Stride Frequency (strides/s)	Limb Stance Phase (% of stride)	Suspension Phase (% of stride)
Adult	RH,RF, LH,LF	Right/Left Bipedal	1.2-1.8	1.5-1.9	0.8-1.1	65-75%	0
6-8 mo			0.6 -1.8	1.4	0.98		

(Leach and Cymbaluk, 1986; Barrey, 2001)

Table 4. Walk parameters in adults and foals between 6 and 8 mo of age.

Collected, Medium and Extended Walk. The collected, medium and extended walk are variations of the walk required of under saddle dressage horses. Medium and extended walk are similar to each other. Stride (1.73-1.82 m) and step lengths are longer than in collection and similar to un-mounted walk variables (Clayton, 1995; Barrey, 2001). Medium walk speed falls within the range of normal un-mounted speeds, while extended walk is slight faster (Clayton, 1995). Over-stride distances are positive in both medium and extended walk, meaning that hind hoofs strike the ground ahead of contralateral fore hoof prints. A regular 4-beat walk has equal timing between lateral and diagonal footfalls. However at the extended walk, irregularities to this rhythm were noted, with the gait becoming more lateral, in a majority of well trained dressage horses (Clayton, 1995; Hodson et al., 1999).

The collected walk is slower (1.37 m/s) and covers less ground. Hindlimb stance duration is greater than forelimb stance duration in all three variations; however, this difference is greatest in the collected walk (Clayton, 1995; Hodson et al., 1999). The collected walk is characterized by shorter step lengths and no over-stride (Clayton, 1995; Hodson et al., 1999).

Effects of Age. Little research has been done to investigate the effects of age or growth on gait parameters, and most have focused on the trot (Back et al., 1993, 2002; Cano et al., 2001). Other research has focused on the value of foal kinematics for predictors of adult trot kinematics (Back et al., 1995) and foal jumping capacity and form as a predictor of adult jumping performance (Bobbert et al., 2005). In Shetland ponies, Dutch warmbloods and Andalusian foals, stride length and duration of the trot increased with age (Back et al., 1994b; Cano et al., 2001; Back et al., 2002). Fore and hindlimb stance duration at the trot are reported to increase significantly between 4 and 36 mo of age in Andalusian and Dutch warmblood foals (Back et al., 1994b; Cano et al., 2001). Increasing wither height during growth is likely responsible for increased stride length and stance durations (Back et al., 1994b; Galisteo et al., 1998). Some work has been done to quantify the flat walk of growing Tennessee Walking horse foals and yearlings (Nicodemus and Clayton, 2003; Nicodemus and Holt, 2003). While similar kinematic changes as seen in warmbloods at the trot can be expected at the walk, no research quantifying changes of the walk in non-gaited breeds during growth is currently available.

CHAPTER III

Growth and Conformation Changes in Suckling and Weanling Warmblood Foals

S.F. Denham[1], W.B. Staniar[1], J.J. Dascanio[2], and R.K. Splan[1]

[1]Department of Animal and Poultry Sciences, Virginia Tech, Blacksburg, VA

[2]Large Animal Clinical Sciences, Virginia-Maryland Regional College of Veterinary Medicine, Blacksburg, VA

Abstract

The objective of this study was to quantify conformation changes in 13 warmblood foals during the first year of growth. Foals were photographed with skin markers placed on the left side over 14 palpable bone and joint locations at 7 d of age and bi-weekly until weaning. A final session occurred in January of the foals' yearling year. Linear measurements included length of neck, scapula, humerus, radius, third metacarpus, front pastern, back, ilium, femur, tibia and third metatarsal length as well as wither and hip height. Angular measurements recorded were scapula, humerus, shoulder, front fetlock, ilium, femur, hip, stifle, tibia and hock angles. Repeated measures analyses were used to compare trait means between age classes. As expected, wither height, hip height, neck length and back length increased from 1 wk to post-weaning. Front cannon length increased between 1 and 7 wk, but not after. Hind cannon length was significantly longer post-weaning than at all younger ages except 23 wk. Hock, tibia and femur angles were more extended in older foals. Front fetlock, scapula and ilium angles did not change across time periods. In agreement with previous reports, wither and hip heights were positively correlated with several bone lengths across ages. Distance out behind was correlated with tibia angle at virtually all ages. Front fetlock angle was not correlated with scapula angle at any age. Warmblood breed registries commonly evaluate pre-weaning foal conformation quality, and resulting scores can heavily influence monetary value of these animals. Characterizing growth rate and conformation changes is a first step towards predicting the best age to evaluate foals and understanding how foal conformation predicts adult conformation. Identifying normal growth rates also aids the development of healthy management practices which may help prevent developmental diseases.

Introduction

Conformation has long been considered an important indicator of performance and soundness (Holmstrom, 2001). The relationship between conformation and soundness is also well recognized (Ross, 2003). Horse trainers, veterinarians and owners all have an interest in understanding ideal equine conformation and how it should be evaluated.

Scientific investigations into relationships between conformation and gait, performance and orthopedic health have confirmed important connections between these traits. Angular limb conformation has a significant influence on gait kinematics (Back et al., 1996). Comparisons between average horses and elite athletes of varying disciplines reveal significant conformational differences between groups (Holmstrom et al., 1990; Koenen et al., 1995). Kinematic traits which are correlated with angular limb conformation are also correlated with superior gait quality and performance (Holmstrom et al., 1995; Back et al., 1996).

Limb conformation is also related to lameness and orthopedic health (Ross, 2003) and conformational analysis is often an early step in lameness exams (Belloy and Bathe, 1996). Many conformation faults have been positively correlated with injury occurrence among warmbloods and racing breeds (Magnusson, 1985c; Holmstrom and Philipsson, 1993; Anderson et al., 2004; van Weeren and Crevier-Denoix, 2006).

The importance of conformation makes it an important criterion when selecting potential top equine athletes. Earlier selection of top animals for further training can avoid economic losses through the training of incapable prospects. The conformation of warmblood foals is often evaluated by breed registries at a young age. Foal inspection scores for conformation, gait quality and overall development are considered by industry as indicators of potential. Also, this subjective evaluation system allows breed registries to insure that breeding goals are met. Breeders also use these scores as indicators of breeding success and economic value of the offspring.

The evaluation of conformation at a young age is useful, however significant differences between foal and adult conformation have been reported (Magnusson, 1985a; Back et al., 1995). Yet, how conformation changes during growth has not been thoroughly investigated. We still lack a clear understanding of how foal conformation predicts or relates to adult conformation. Thus, the purpose of this study was to quantify the linear and angular conformation changes occurring during the early growth of warmblood foals.

Materials and Methods

Horses

Thirteen warmblood foals (3 colts and 10 fillies) born between March 6 and May 16, 2006 were utilized in this study. All foals were born and raised at the Virginia Tech Smithfield Horse Center in Blacksburg, Virginia. Mares and foals were group housed on native grass pastures and supplemented with a balanced ration concentrate to maintain mare body condition score (BCS) of 6-7 pre-weaning and a foal BCS of 5-6 post-weaning.

Photographs

Photographs were taken at 7 d of age and bi-weekly until weaning. One final photograph session was taken in January of 2007 for post-weaning values. Self adhesive skin markers were placed over 14 palpable bone and joint markers on the animal's left side by a single trained evaluator each recording session (Figure 1) in a technique modified from that described by Holmstrom et al. (1990). All photographs were taken in the same location, on level concrete covered by 13mm rubber matting. Foals were placed in a standardized, square position with third metacarpal and metatarsal bones perpendicular to the ground. A meter stick was included in each photo for scaling purposes. The camera lens was placed perpendicular to the foals' body at a height approximately equal to the center of the rib cage. All photos were taken with a Canon EOS digital camera with a 200mm lens. Images were digitally stored until transfer to a computer hard drive for analysis.

Measurements

ImageJ software (Rasband, 1997-2007) was used to take measurements from photographs. The measuring stick included in each photo was used to calibrate to pixels per cm.

The following linear measurements were taken from each photo (Figure 2):

1. Neck length - wing of the atlas to the proximal end of the scapular spine
2. Scapula length - proximal end of the scapular spine to the greater tubercle of the humerus.
3. Humerus length - greater tubercle of the humerus to the lateral epicondyle of the humerus
4. Radius length - lateral epicondyle of the humerus to the lateral prominence of the distal radius
5. Third metacarpal length - metacarpal tuberocity to the distal end of the metacarpus
6. Front fetlock length - distal end of the metacarpus to the coronary band
7. Back length - proximal end of the scapular spine to the dorsal ridge of the ilium tuber coxae
8. Ilium length - dorsal ridge of the ilium tuber coxae to the greater trochanter of the femur
9. Femur length - greater trochanter of the femur to the trochlear ridge of the femur
10. Tibia length - trochlear ridge of the femur to the lateral malleolus of the tibia
11. Third metatarsal length - metatarsal tuberocity to the distal end of the metatarsus
12. Wither height - highest point of wither to ground

13. Hip height - highest point of croup to ground
14. Distance out behind - A vertical line was drawn digitally from the point of the hock upwards. The distance out behind was measured as the horizontal distance between this line and the most caudal point of the buttock. This measurement serves as a quantification of the 'camped out' conformation fault (Ross, 2003).

The following angular measurements were recorded (Figure 3):

1. Scapula - proximal end of the scapular spine to the greater tubercle of the humerus to a line parallel with the ground
2. Humerus - lateral epicondyle of the humerus to the greater tubercle of the humerus to a line parallel with the ground
3. Shoulder - proximal end of the scapular spine to the greater tubercle of the humerus to the lateral epicondyle of the humerus
4. Elbow - greater tubercle of the humerus to the lateral epicondyle of the humerus to the metacarpal tuberocity
5. Front fetlock - metacarpal tuberocity to the distal end of the metacarpus to a line parallel to the ground
6. Ilium - dorsal ridge of the ilium tuber coxae to the greater trochanter of the femur to a line parallel to the ground
7. Femur - trochlear ridge of the femur to the greater trochanter of the femur to a line parallel to the ground
8. Hip - dorsal ridge of the ilium tuber coxae to the greater trochanter of the femur to the trochlear ridge of the femur

9. Tibia - lateral malleolus of the tibia to the trochlear ridge of the femur to a line parallel to the ground
10. Stifle - greater trochanter of the femur to the trochlear ridge of the femur to the lateral malleolus of the tibia
11. Hock - trochlear ridge of the femur to the lateral malleolus of the tibia to the distal end of the metatarsus

Statistical Analysis

Statistical analysis was done using SAS/STAT software (SAS Institute, 2002-2004). Fixed effects of age of sex, dam, parity and foal birth month were tested, but found to be non-significant for virtually all traits and were thus not included in the final model. Data were grouped by week of age. Mean days of age at each age group are presented in Table 1. Repeated measures analyses were used to compare trait means between age groups. Sidak adjustments were performed to account for multiple comparisons. Pearson's correlations were used to investigate relationships among traits within age groups. Significance is reported at the $P < 0.05$ level.

Results

Changes Due to Age

Linear Conformation. Mean linear measurements at all investigated ages are presented in Table 2. Total growth percentage increase in length for all linear conformation traits are listed in descending order in Table 3.

As expected, all linear conformation traits increased significantly during the study. Mean wither height (Fig 4) at 1 wk was 104.7 ± 1.7 cm and increased to 143.6 ±

1.6 cm post-weaning. Hip height (Fig 5) increased from 106.7 ± 1.7 cm to 149 ± 1.9 cm over the investigated ages. Both wither and hip height increased fastest until 7 wk. From 1 to 7 wk significant differences existed between means at each measured age. However, between 7 and 9 weeks of age, while heights increased, this change was not significant. From 7 to 17 wk of age, both wither and hip heights were only significantly different between every other age group. There was no statistical difference between mean wither heights at 17, 19 and 21 wk. Hip height growth also slowed and no significant growth occurred between 15, 17 and 19 wk or 17, 19 and 21 wk. Both wither and hip height differences were significant between 19 and 23 wk and post-weaning values were significantly larger than all previous ages. Hip heights exceeded wither height by an average of 3.78 ± 0.28 cm over the studied ages. This difference was greatest between 13 and 17 wk (4.75 to 5.36 cm).

Neck length (Fig 6) increased from 34.6 ± 0.62 cm to 62.8 ± 0.81 cm over the investigated ages. Neck length did not increase significantly between 1, 3 and 5 wk. However, neck length did significantly increase between 3 and 7 wk. After 3 wk, significant differences existed between every-other age group. At 15 wk of age, neck length increases slowed. No significant differences were noted between 15, 17 and 19 wk. While means did increase slightly between 17, 19, 21 and 23, no significant differences exist. Post-weaning neck length was significantly longer than all previously investigated ages ($P< 0.0001$).

Back length (Fig 7) increased from 36.9 ± 0.57 cm to 70.1 ± 1.10 cm from 1 wk to post-weaning. Increases were significant between 1 and 3 wk. However after 3 wk, differences were not significant between consecutive ages. No statistical difference existed between back lengths at 15, 17 and 19 wk or 17, 19, 21 and 23 wk. Post-weaning back length differed significantly from all other investigated ages ($P < 0.0001$).

During this study, scapula length (Fig 8) increased from 23.1 ± 0.60 cm to 37.9 ± 0.60 cm. By 3 wk, differences were only significant between every-other measurement period. Scapula length did not increase significantly between 7, 9 and 11 wk. However, differences between 9 and 13 wk were significant. Growth slowed again after 13 wk and no differences were seen between scapula length at 13, 15, 17 and 19 wk or 15, 17 and 19 wk. However, means at 19 and 21 wk were statistically different. Scapula length post-weaning was significantly larger than at all previous ages ($P < 0.0001$).

Humerus length (Fig 9) increased from 12.5 ± 0.30 cm to 17.9 ± 0.81 cm from 1 wk to post-weaning. No significant growth occurred between 1, 3 and 5 wk. Humerus length at 5 wk only differed significantly from trait means at 21 and 23 wk and post-weaning. From 7 to 19 wk, humerus length only differed from post-weaning values. Twenty-one, 23 wk and post-weaning values did not differ.

Radius length (Fig 10) increased from 28.4 ± 0.60 cm at 1 wk to 46.41 ± 0.80 cm post-weaning. Significant growth occurred during the first 3 wk. However, statistical differences were not noted between 3, 5 and 7 wk measurements. Measurements at 7 wk did not differ from those at 9 and 11 wk, but were significantly lower than values at 13 wk and older. Significant growth occurred between 9 and 15 wk and 11 and 15 wk. However, at 13 wk and older differences were only noted between every third measurement period. Post-weaning values differed from all early ages ($P \leq 0.0001$).

Both third metacarpal (Fig 11) and third metatarsal length (Figure 12) showed little growth compared to overall heights and other long bone measurements over the studied time period. Metacarpal length increased from 17.3 ± 0.36 cm to 19.0 ± 0.40 cm. Metacarpal length was significantly different between 1 and 7 wk and older. However, no other significant differences existed. Metatarsal length increased from 22.0 cm ± 0.41 cm to 23.9 ± 0.60 cm from 1 wk to post-weaning. Increases in metatarsal length were not statistically significant between 1 and 23 wk. However, post-weaning length was longer than all values 21 wk and younger ($P < 0.03$).

Front fetlock length (Fig 13) results were inconsistent, with mean values at older ages sometimes being less than those younger ages. As this trait was measured using the marker placed over the distal end of the metacarpal bone and the coronet band, which was unmarked, this is likely due to measurement errors. These errors make it difficult to discern the true growth rate for this trait. Fetlock length increased from 13.1 ± 0.26 cm at 1 wk to 15.6 ± 0.39 cm post-weaning. Values at 1 and 3 wk were significantly less that those at 9 wk and older. Fetlock length at 7 wk was less than those at 13 wk and older. However, after 13 wk of age, no statistically significant increases occurred.

Ilium length (Fig 14) increased from 20.4 cm ± 0.50 cm at 1 wk to 32.2 ± 0.92 cm post-weaning. Growth was fastest between 1 and 3 wk of age and gradually slowed. While 3 and 7 wk means differed significantly, no statistical increases occurred between 5, 7 and 9 wk. Ilium length at 7 wk was significantly lower than values at 15 wk and older. Mean length at 15 wk was significantly less than post-weaning values, but no other ages. While all means 21 wk and younger differed from post-weaning, there was no difference between 23 wk and post-weaning.

Femur length (Fig 15) increased from 17.7 ± 0.59 cm to 26.1 ± 0.48 cm over the investigated ages. The majority of growth occurred between 1 and 7 wk. Mean femur length at 17 wk was significantly longer than all means before 9 wk. From 11 wk to 19 wk, values only differed significantly from post-weaning ($P < 0.02$). However both 21 and 23 wk lengths were not significantly different from post-weaning lengths.

Tibia length (Fig 16) growth rate was fairly consistent and similar to that of the radius. In total, tibia length increased from 31.9 ± 0.84 cm at 1 wk to 46.0 ± 0.95 cm post-weaning. Through-out growth, except at 11 wk, significant growth occurred at 6 wk intervals. Tibia length at 11 and 15 wk differed significantly, possibly indicating a faster growth over this period. Post-weaning tibia length was significantly larger than all ages except 23 wk ($P < 0.01$).

The distance out behind (Fig 17) decreased significantly between 1 and 5 wk. Mean distance out behind at 3 wk was significantly greater than at 13 wk and older. However by 5 wk of age, while this value continued to decrease, the only significant differences were between 5 and 15 wk and 7 and 15 wk. Foals displayed the least camped out conformation at 15 wk.

Angular Conformation. Table 4 displays mean angular measurements across ages. Scapula angle ranged between 55° and 63° over the investigated ages (Fig 18). While scapula angle was highest (most upright) at the post-weaning age, this was only significantly different from means at 7 and 9 wk.

Humerus angle (Fig 19) significantly decreased between 1 and 13 wk and almost all older ages. Mean humerus angle was lowest at the post-weaning age group and significantly lower than values at 1, 7 and 9 wk. Both shoulder (Fig 20) and elbow joint angles (Fig 21), which are related to the humerus angle, tended to be smaller at older ages, but differences were non-significant. No significant changes in front fetlock angle (Fig 22) occurred during the investigated ages.

In the hindlimb, no significant changes were noted in ilium angle (Fig 23). However, the femur angle (Fig 24) increased with age, becoming more upright. After Sidak adjustments differences were non-significant. Before adjustments, femur angle was significantly higher between 1 and 23 wk and post-weaning values. Hip angle (Fig 25) therefore increased with age, but differences were only significant between 7 wk and post-weaning values. Stifle angle (Fig 26) also increased with age with significant differences between means at 1 and 15 wk, 1 wk and post-weaning and 7 wk and post-weaning. Before Sidak adjustments, means at virtually all ages prior to 11 wk were significantly less than those at 15 wk and older.

Tibia angle (Fig 27) increased with age, becoming more upright. However these differences were not significant. Again, before adjusting for multiple comparisons, stifle angle was significantly different ($P < 0.05$) between 1 and all ages older than 15 wk. The hock angle (Fig 28) also increased, becoming straighter with age. Hock angle at 1 wk was significantly larger than at 15, 21 wk and post-weaning.

Correlations Within Ages

Due to the small sample size of this study, significant correlations between traits were rare. Strong positive correlations existed between wither and hip height at all investigated ages (Table 5). Wither height also positively correlated with most long bone lengths at all investigated ages (Table 5). Distance out behind correlated to tibia angle at virtually all ages ($r = 0.62$ to 0.97, $P < 0.02$). Strongest correlations between these traits occurred in the two oldest age groups. Correlations between scapula and fetlock angle were non-existent at almost all ages. At 1 wk, but no later ages, front fetlock angle was positively correlated (r = 0.60, P = 0.03) with wither height. It is likely that other significant correlations were undetectable due to the lack of statistical power.

Discussion

As expected, in almost all traits the most significant growth occurred early during the foals' development. Previous growth research in various horse breeds has established that for many traits, including wither and hip heights, body weight, body length and limb lengths growth occurs fastest during the first mo of growth (Green, 1969,1976; Hintz et al., 1979; Fretz et al., 1984; Thompson and Smith, 1994; Thompson, 1995).

Hip heights exceeded wither height at investigated all ages. Other researchers have noted this in growing Standardbreds (Magnusson, 1985b) and Thoroughbreds (Thompson, 1995). Wither height exceeding hip height is considered a desirable trait in adult horses, as an uphill build is associated with better balance and athletic ability (Hedge et al., 2004). In the warmblood foals of this study, hip heights exceeded wither height by an average of 3.8 cm through-out the study with the greatest difference between 15 and 19 wk. By post-weaning measures the difference between wither and hip height had decreased, however foals were still down-hill. Holmstrom et al. (1990) reported wither height exceeding hip height by an average of 2.5 cm in a study of 365 adult Swedish warmblood horses. Therefore, it can be expected for down-hill conformation in most young warmbloods to eventually be outgrown. Growth studies of warmbloods to later ages are necessary to discern at what age wither height can be expected to exceed hip height.

At virtually all ages prior to post-weaning measurements, wither and hip height positively correlated with scapula, fetlock, front cannon and hind cannon lengths. Other studies have found that most long bone lengths moderately correlated with wither height across ages, supporting the theory that horses are proportional (Magnusson, 1985b; Anderson and McIlwraith, 2004; Weller et al., 2006b). However, Weller et al. (2006b) found no correlations between height and cannon lengths in a group of adult Thoroughbred race horses. In the present study, the correlations between heights and several lengths including femur, tibia, ilium and radius were either inconsistent or virtually non-existent. The small population size utilized in this study and some differences in measurement technique are likely causes of the lack of correlation between traits and statistical significance.

Total neck length increased by 81.7% over the investigated ages and increased fastest between 3 and 9 wk. However, neck length is highly variable based on the animal’s stance. While every attempt was made to standardize animal stance, it is possible that measurement error occurred due to a lack of consistent positioning. The inconsistency in measurement results, such as mean neck length at 19 wk being shorter than means at 17 wk is likely due to error establishing an identical position at each recording session.

Back length nearly doubled (89.8%) over the investigated ages, and growth was fastest during the first 5 wk. In Thoroughbred foals, body length (measured from point of shoulder to point of buttock) increased at a similar rate to wither and hip height, with the fastest growth occurring during the first mo (Thompson, 1995). Between 14 and 252 d, body length in Thoroughbreds increased 64.9% (Thompson, 1995). However, methodology differences make comparisons between this study and Thompson's difficult. Magnusson (1985a) reported only a 23% increase in body length in Standardbred colts from 6.5 to 25.5 mo, perhaps implying that growth slows during post-weaning ages. Again, differences in measurement techniques make direct comparison of results convoluted.

Both neck and back length strongly positively correlated ($r = 0.82$ to 0.95, $P < 0.0005$) with each other as well as both wither and hip heights at 9 wk. However at many other ages these relationships were insignificant. Anecdotally, it is believed that 3 mo of age is a good time to evaluate foal conformation. It is possible that the strength of these correlations at this age imply a greater degree of conformational balance during the 3rd mo of age. However, the small number of animals in this study could also result in insignificant correlations at other ages.

Scapula growth rates were fairly consistent with wither and hip, with the fastest growth occurring between 1 and 3 wk. Percentage of scapula growth was higher than any other front limb segment. This finding is consistent with reports during later growth of Standardbred foals (Magnusson, 1985b). Increasing scapula length therefore contributes to increased wither heights. Scapula angle also significantly increased during growth. Several other researchers have reported increasing scapula inclination with age (Magnusson, 1985b; Back et al., 1995; Anderson and McIlwraith, 2004). Other researchers have speculated that increasing scapular inclination also contributes to increased wither heights (Anderson and McIlwraith, 2004).

A laid back scapula anecdotally is considered a desirable conformation trait and scapular inclination is negatively correlated with subjective scores for walk under saddle and total gait score in adult Swedish warmbloods (Holmstrom and Philipsson, 1993). Changing scapula angle with age should be considered when evaluating foal conformation for future performance, as this angle changes significantly during growth. Additional studies are needed to identify when scapular changes are complete and how consistent these changes are between horses to allow for accurate prediction of adult conformation from foal values.

Of all forelimb conformational traits, a long humerus is most strongly correlated with good gait quality (Holmstrom and Philipsson, 1993). Horses competing at the highest level of dressage, a sport heavily emphasizing gait quality, had significantly longer humeri bones than both elite show jumpers and average riding horses (Holmstrom et al., 1990). In the present study, both humerus length and angle changed significantly during the first 9 mo of growth. However, total humerus growth was minimal compared to other proximal limb bones. Humerus angle plots (Figure 19) reveal inconsistent patterns. Previous investigators have found that traits measured using the humerus markers yield highly variable results (Weller et al., 2006a). Marker placement error possibly influenced the results of this trait. Low population numbers and the high number of ages compared, made statistical significance after Sidak adjustments low. Before adjustments, humerus angle at 13 wk and older was significantly flatter than values at 1 wk. When considering the joints as a simple hinge system, it makes sense that if the scapula and radius grow at a faster rate than the humerus, the humerus angle would become more horizontal. Other growth studies have not investigated the changes in humerus angle separate from changes in total shoulder angle. However, previous studies (Magnusson, 1985b; Back et al., 1995; Anderson and McIlwraith, 2004) have found both shoulder and elbow joint angles to increase with age, which is not in agreement with the current study. Research in larger populations is needed to confirm what the normal humerus and elbow angle changes are during growth.

Total percentage of third metacarpal and metatarsal growth was lower than any other measured body segment. Results for metacarpal and metatarsal growth rates are in agreement with previous research which reported that metacarpal growth is minimal and plateaus earlier than other long bone growth (Magnusson, 1985b; Anderson and McIlwraith, 2004). In Thoroughbreds, metatarsal growth was nominal, and only significant between 1 and 2 yr, implying the metatarsal bone grows slowly and later than the third metacarpal bone (Anderson and McIlwraith, 2004). While the current study contained only a small number of animals, it is likely that results are accurately in agreement with previous work.

Epiphyseal plates, where longitudinal bone growth occurs, have been shown to close between 7 and 18 mo in the third metacarpal bones (Tohara, 1950; Myers and Emerson, 1966; Rooney, 1963; Fretz, 1984). This is earlier than the closure time for radial epiphyseal plates, which close between 2 and 3.5 yr (Myers and Emerson, 1966; Rooney, 1963; Fretz, 1984). Investigation of epiphyseal plate closures therefore supports the findings that distal limb growth finishes earlier than proximal limb growth. However, directly comparing these studies of growth is complicated. Growth research using skin markers and photographs or live animal measurements often use landmarks which span multiple growth plates as well as some joint space. Therefore, looking solely at specific plate closure times does not compare directly to measurements of an entire limb segment.

Never the less, it is not surprising that both methods reveal earlier slowing of growth in the distal limb bones.

Over all investigated ages except 7 and 11 wk, front fetlock angle was not correlated with scapula angle, contrary to the anecdotal belief that these two angles are the same. At 7 wk there was a moderate positive correlation and at 11 wk there was a moderate negative correlation between these traits. This inconsistency further disputes the concept that scapula and fetlock angles should match. Anderson and McIlwraith (2004) also found either no or weak positive correlations between these traits.

At 1 wk, but no later ages, front fetlock angle was moderately positively correlated to wither height. It is possible that increased the joint flexion of larger foals during late gestation causes this more upright fetlock angle. This condition resolved by 3 wk and, and no significant correlations between these traits existed at older ages.

In the current study, front fetlock angle did not change significantly over the investigated ages. However, research in larger populations report a more sloping fetlock angle with age until 2 yr, likely due to increasing body weight (Anderson and McIlwraith, 2004). While not investigated in the current study, hoof angle is also reported to become less upright with age (Anderson and McIlwraith, 2004; Kroekenstoel et al., 2006).

The correct alignments of the hoof-pastern axis and the third phalanx are important for long-term soundness (Parks, 2003). In Thoroughbred race horses, the incidence of deep digital flexor tendon injury increased with increasing, upright, fetlock angles (Weller et al., 2006c). Comparison of subjective human evaluation and radiographic findings in growing foals reveals that visual investigation does not accurately identify changes in either the hoof-pastern or distal phalanx alignments

(Kroekenstoel et al., 2006). Radiographic evaluation of the third phalanx alignment within the hoof revealed decreasing differences between hoof and bone angles with age (Kroekenstoel et al., 2006). The methodology of the current study did not allow for detection of important alignment changes occurring within the hoof capsule.

Of the hindlimb segments, total percentage of ilium growth was the greatest. However, unlike the scapula, ilium length was not correlated to wither or hip height at most ages. Due to the relatively horizontal positioning of the ilium, it is unlikely that changes in ilium length are most responsible for increasing hip heights. No significant change in ilium angle occurred during growth while femur angle became more upright with age. In both Standardbreds (Magnusson, 1985b) and Dutch warmbloods (Back et al., 1995), the hip joint was more extended in older foals, possibly in part due to changing femur angle. Flatter ilium and smaller, more forward sloping femur angles have a positive effect on the total score for conformation and gait in 4-year-old warmbloods (Holmstrom and Philipsson, 1993). In adult warmbloods, a straighter femur angle has been associated with increased occurrence of lameness (Holmstrom, 2001). This is possibly due to increased concussion within the stifle and/or hip joints. As femur angle is a trait related to gait quality, performance and soundness, differences between foal and adult values should be considered when evaluating young horses' conformation.

Tibia growth was significant between 11 and 17 wk, at time period when many other traits showed no significant increases. The greatest difference between wither and hip height (wither < hip) occurred between 13 and 17 wk. Perhaps increased or maintained tibia growth during an age when front limb bone growth is slowing is a cause of this increased difference between total wither and hip height.

Camped out conformation (Figure 29) is considered a significant conformational fault and animals displaying this trait are often avoided as athletic prospects (Magnusson, 1985b; Mawdsley et al., 1996). This fault can result in poor athletic ability and lameness in the tarsus and plantar soft tissues (Ross, 2003). Foals became significantly less camped out from 1 to 15 wk. The distance out behind is moderately or strongly positively correlated with tibia angle at virtually all ages. Tibia angle became significantly more upright with age, resulting in the less camped out stance in older foals.

Hock angle became significantly larger, or straighter, with age. The results of this study are not in agreement of studies in both Standardbreds (Magnusson, 1985b) and Dutch warmbloods (Back et al., 1995) which found no significant changes in hock angle with age. Although, these studies did investigate horses at an older age than the current study. Holmstrom et al. (1990) found that 4 year old Swedish warmblood horses displayed a significantly smaller hock angle compared to older riding horses.

Overly straight hock angles (post legged) and overly angulated (sickle) hocks are considered a serious fault (Ross, 2003). Extreme hock angles affect the concussive forces in the hock. However current literature is conflicting as concussive forces are reported highest in both small (Gnagey et al., 2006) and large (Back et al., 1996) hock angles. Methodology differences between the two studies make comparisons unclear. Actual joint angle ranges for ‘small’ and ‘large’ classifications vary between studies. When compared to average riding horses, elite dressage and jumping horses had a straighter hock angle (Holmstrom et al., 1990). Yet, the “straight” hock angle ranges in Holmstrom’s work (1990) corresponded with the “intermediate” range reported by

Gnagey (2006). An optimal hock angle has yet to be established; however there are clearly negative consequences of extreme hock angulations.

With the development and application of better technology, conformation and growth research has opened a new avenue of health and soundness management of equine athletes. Equine conformation is linked to performance and orthopedic health (Back et al., 1996; Dolvik and Klemetsdal, 1999; Anderson et al., 2004). Normal growth rates are an important factor in avoiding developmental disease (Vervuert et al., 2005). Growth, conformation and performance are all also influenced by genetics (Pool-Anderson et al., 1994; Koenen et al., 1995; Barneveld, 1997; Koenen et al., 2004; Love et al., 2006) Future investigation into the effects of growth rates on orthopedic health, and the effects of nutrition, genetics and environment on growth will help to establish normal, healthy growth patterns in warmbloods raised in North America. Additional quantification of linear and angular conformation changes during growth and the understanding of how conformation relates to performance and health are a valuable step towards breeding, managing and maintaining healthier, more successful equine athletes.

Age Group	Mean Days of Age	SEM
1 wk	7	0.12
3 wk	19	0.91
5 wk	32	0.90
7 wk	46	0.84
9 wk	59	0.86
11 wk	72	0.83
13 wk	87	0.91
15 wk	102	0.96
17 wk	116	0.95
19 wk	129	1.01
21 wk	143	0.95
23 wk	156	1.51
39 wk (post-weaning)	272	5.84

Table 1. Mean days of age for each age group

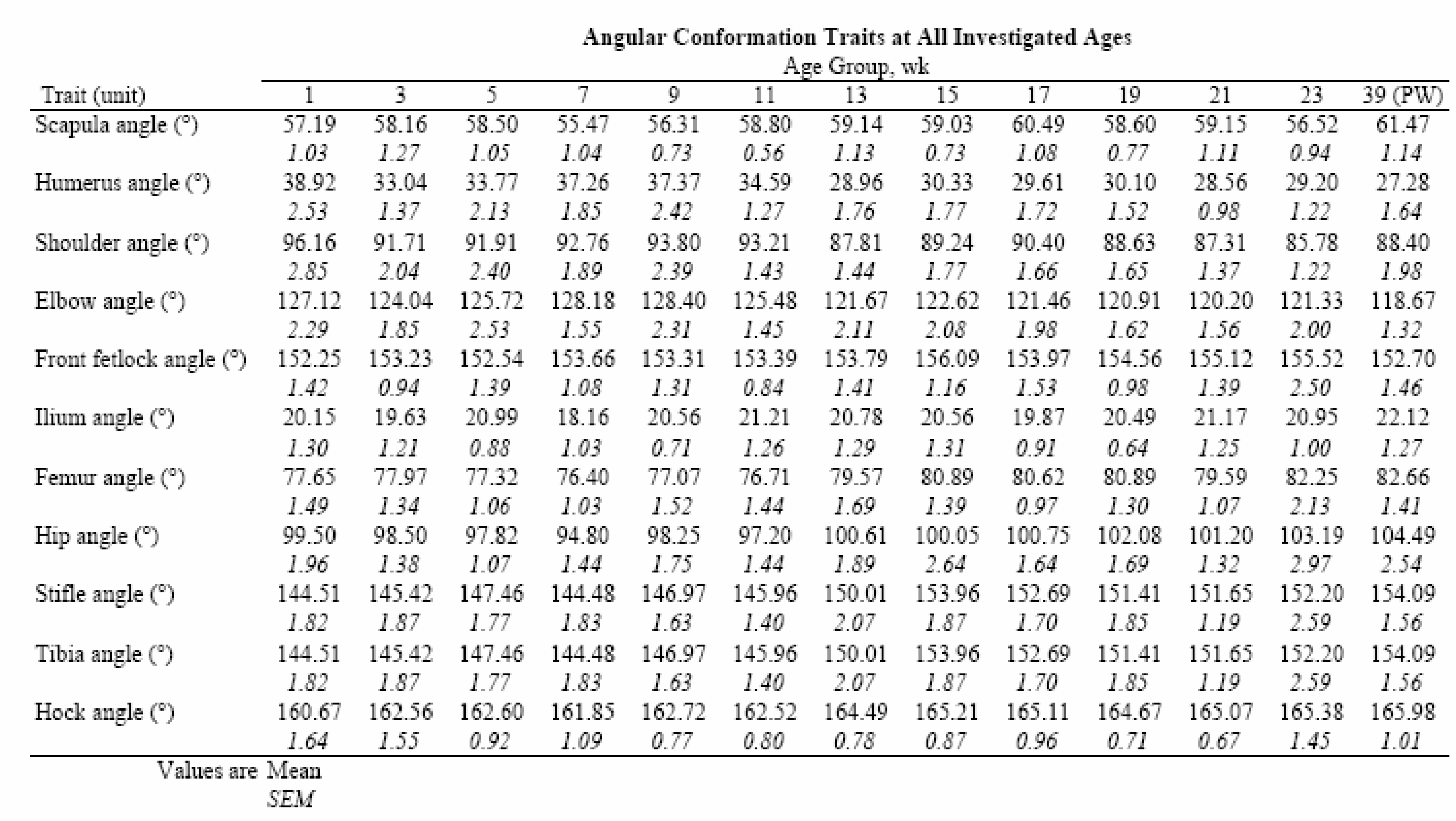
Linear Conformation Traits at All Investigated Ages

	Age Group, wk												
Trait (unit)	1	3	5	7	9	11	13	15	17	19	21	23	39 (PW)
Wither height (cm)	104.70	109.37	113.29	117.44	120.15	122.09	125.17	127.91	129.33	131.11	132.61	134.71	146.27
	1.72	*1.62*	*1.37*	*1.42*	*1.61*	*1.39*	*1.58*	*1.51*	*1.54*	*1.32*	*1.66*	*2.09*	*1.60*
Hip height (cm)	106.80	111.87	116.47	120.58	123.46	126.69	129.92	132.66	134.69	135.57	136.69	138.82	149.04
	1.71	*1.59*	*1.36*	*1.55*	*1.54*	*1.41*	*1.50*	*1.79*	*1.65*	*1.42*	*1.76*	*2.14*	*1.88*
Neck length (cm)	34.57	36.17	36.94	39.93	42.02	44.69	46.58	48.31	50.28	50.01	52.90	52.61	62.80
	0.62	*0.86*	*1.02*	*0.53*	*0.87*	*0.94*	*0.82*	*0.97*	*1.29*	*0.85*	*0.91*	*0.93*	*0.81*
Back length (cm)	36.93	40.95	43.94	46.58	48.95	51.86	54.29	56.04	58.94	58.93	60.82	61.75	70.12
	0.57	*0.86*	*0.91*	*0.83*	*0.73*	*0.77*	*0.90*	*1.07*	*0.86*	*0.89*	*0.82*	*0.55*	*1.07*
Distance out behind (cm)	6.36	4.80	3.45	3.39	2.61	2.15	1.40	0.53	0.78	1.02	1.01	1.19	1.19
	1.01	*0.65*	*0.54*	*0.67*	*0.61*	*0.73*	*0.84*	*0.80*	*0.78*	*0.66*	*0.78*	*1.47*	*1.04*
Scapula length (cm)	23.12	25.02	26.05	27.45	28.28	29.13	30.34	31.21	31.87	31.69	33.07	33.80	38.00
	0.61	*0.54*	*0.32*	*0.52*	*0.47*	*0.45*	*0.51*	*0.51*	*0.40*	*0.44*	*0.30*	*0.36*	*0.60*
Humerus length (cm)	12.47	12.34	13.83	14.65	15.03	15.19	15.11	15.63	15.50	15.65	16.07	16.57	17.95
	0.30	*0.47*	*0.49*	*0.34*	*0.42*	*0.65*	*0.58*	*0.73*	*0.47*	*0.49*	*0.58*	*0.60*	*0.81*
Radius length (cm)	30.68	33.20	33.71	34.89	36.50	37.06	38.74	39.65	40.38	41.25	41.59	42.06	46.41
	0.60	*0.65*	*0.52*	*0.41*	*0.59*	*0.67*	*0.56*	*0.56*	*0.39*	*0.28*	*0.48*	*0.51*	*0.80*
Front cannon length (cm)	17.29	18.03	18.11	18.54	18.30	18.19	18.45	18.49	18.59	18.43	18.51	18.81	19.03
	0.36	*0.33*	*0.31*	*0.34*	*0.32*	*0.28*	*0.28*	*0.37*	*0.32*	*0.25*	*0.33*	*0.43*	*0.40*
Front fetlock length (cm)	13.08	13.12	14.03	13.74	14.23	14.19	14.74	15.08	14.98	15.17	15.42	15.02	15.60
	0.26	*0.23*	*0.33*	*0.29*	*0.34*	*0.30*	*0.35*	*0.30*	*0.27*	*0.28*	*0.32*	*0.38*	*0.39*
Ilium length (cm)	20.37	22.81	23.94	25.42	25.94	26.36	26.66	27.74	27.92	28.03	29.23	29.62	32.23
	0.51	*0.44*	*0.42*	*0.54*	*0.45*	*0.47*	*0.53*	*0.53*	*0.68*	*0.34*	*0.56*	*0.83*	*0.92*
Femur length (cm)	17.66	19.17	20.19	21.56	21.70	22.86	23.02	22.67	24.19	23.56	23.93	24.06	26.11
	0.59	*0.47*	*0.51*	*0.59*	*0.48*	*0.54*	*0.51*	*0.40*	*0.40*	*0.53*	*0.61*	*0.68*	*0.48*
Tibia length (cm)	31.87	33.12	33.93	35.64	36.46	37.69	38.59	40.16	40.70	42.21	42.71	43.34	45.98
	0.84	*0.77*	*0.61*	*0.61*	*0.72*	*0.67*	*0.62*	*0.74*	*0.64*	*0.74*	*0.56*	*0.65*	*0.95*
Hind cannon length (cm)	22.03	22.50	22.21	22.28	22.63	22.60	22.85	23.06	22.58	22.78	22.56	22.82	23.87
	0.41	*0.36*	*0.42*	*0.28*	*0.32*	*0.40*	*0.30*	*0.30*	*0.42*	*0.21*	*0.42*	*0.38*	*0.60*
Values are	Mean *SEM*												

Table 2. Mean (± SEM) linear measurements by age

Trait	Growth (%)
Back	89.8
Neck	81.7
Scapula	64.4
Ilium	58.2
Radius	51.3
Femur	47.8
Tibia	44.3
Humerus	43.9
Wither Height	39.7
Hip Height	39.6
Front Fetlock	19.2
Third Metacarpal	10.1
Third Metatarsal	8.3

Table 3. Percentage total linear growth over all investigated ages



Angular Conformation Traits at All Investigated Ages

Trait (unit)	Age Group, wk 1	3	5	7	9	11	13	15	17	19	21	23	39 (PW)
Scapula angle (°)	57.19	58.16	58.50	55.47	56.31	58.80	59.14	59.03	60.49	58.60	59.15	56.52	61.47
	1.03	*1.27*	*1.05*	*1.04*	*0.73*	*0.56*	*1.13*	*0.73*	*1.08*	*0.77*	*1.11*	*0.94*	*1.14*
Humerus angle (°)	38.92	33.04	33.77	37.26	37.37	34.59	28.96	30.33	29.61	30.10	28.56	29.20	27.28
	2.53	*1.37*	*2.13*	*1.85*	*2.42*	*1.27*	*1.76*	*1.77*	*1.72*	*1.52*	*0.98*	*1.22*	*1.64*
Shoulder angle (°)	96.16	91.71	91.91	92.76	93.80	93.21	87.81	89.24	90.40	88.63	87.31	85.78	88.40
	2.85	*2.04*	*2.40*	*1.89*	*2.39*	*1.43*	*1.44*	*1.77*	*1.66*	*1.65*	*1.37*	*1.22*	*1.98*
Elbow angle (°)	127.12	124.04	125.72	128.18	128.40	125.48	121.67	122.62	121.46	120.91	120.20	121.33	118.67
	2.29	*1.85*	*2.53*	*1.55*	*2.31*	*1.45*	*2.11*	*2.08*	*1.98*	*1.62*	*1.56*	*2.00*	*1.32*
Front fetlock angle (°)	152.25	153.23	152.54	153.66	153.31	153.39	153.79	156.09	153.97	154.56	155.12	155.52	152.70
	1.42	*0.94*	*1.39*	*1.08*	*1.31*	*0.84*	*1.41*	*1.16*	*1.53*	*0.98*	*1.39*	*2.50*	*1.46*
Ilium angle (°)	20.15	19.63	20.99	18.16	20.56	21.21	20.78	20.56	19.87	20.49	21.17	20.95	22.12
	1.30	*1.21*	*0.88*	*1.03*	*0.71*	*1.26*	*1.29*	*1.31*	*0.91*	*0.64*	*1.25*	*1.00*	*1.27*
Femur angle (°)	77.65	77.97	77.32	76.40	77.07	76.71	79.57	80.89	80.62	80.89	79.59	82.25	82.66
	1.49	*1.34*	*1.06*	*1.03*	*1.52*	*1.44*	*1.69*	*1.39*	*0.97*	*1.30*	*1.07*	*2.13*	*1.41*
Hip angle (°)	99.50	98.50	97.82	94.80	98.25	97.20	100.61	100.05	100.75	102.08	101.20	103.19	104.49
	1.96	*1.38*	*1.07*	*1.44*	*1.75*	*1.44*	*1.89*	*2.64*	*1.64*	*1.69*	*1.32*	*2.97*	*2.54*
Stifle angle (°)	144.51	145.42	147.46	144.48	146.97	145.96	150.01	153.96	152.69	151.41	151.65	152.20	154.09
	1.82	*1.87*	*1.77*	*1.83*	*1.63*	*1.40*	*2.07*	*1.87*	*1.70*	*1.85*	*1.19*	*2.59*	*1.56*
Tibia angle (°)	144.51	145.42	147.46	144.48	146.97	145.96	150.01	153.96	152.69	151.41	151.65	152.20	154.09
	1.82	*1.87*	*1.77*	*1.83*	*1.63*	*1.40*	*2.07*	*1.87*	*1.70*	*1.85*	*1.19*	*2.59*	*1.56*
Hock angle (°)	160.67	162.56	162.60	161.85	162.72	162.52	164.49	165.21	165.11	164.67	165.07	165.38	165.98
	1.64	*1.55*	*0.92*	*1.09*	*0.77*	*0.80*	*0.78*	*0.87*	*0.96*	*0.71*	*0.67*	*1.45*	*1.01*

Values are Mean
SEM

Table 4. Mean (± SEM) angle measurements by age

	Correlations with wither height by age												
	Age Group, wk												
	1	3	5	7	9	11	13	15	17	19	21	23	39 (PW)
Hip height	0.97***	0.96***	0.95***	0.97***	0.96***	0.94***	0.98***	0.84***	0.97***	0.96***	0.95***	0.97***	0.93***
Scapula length	0.79**	0.82***	0.49†	0.76***	0.76**	0.70**	0.75**	0.76**	0.79**	0.89***	0.30	0.74*	0.63†
Humerus length	0.65*	0.43	0.63*	0.61*	0.56*	0.35	0.90***	0.71*	0.77**	0.71**	0.73*	0.61	0.36
Radius length	0.66*	0.64*	0.22	0.68*	0.49†	0.66*	0.61*	0.25	0.37	0.56†	0.58†	0.23	0.72*
Front cannon length	0.73**	0.75**	0.73**	0.50†	0.86***	0.87***	0.75**	0.83***	0.77**	0.58*	0.72*	0.76*	0.41
Ilium length	0.61*	0.69**	0.59*	0.36	0.35	0.71**	0.63*	0.25	0.52†	0.25	0.47	0.15	0.53
Femur length	0.73**	0.84***	0.48†	0.32	0.61*	0.40	0.35	0.50†	0.37	0.56	0.76**	0.71*	-0.06
Tibia length	0.63*	0.25	0.37	0.75**	0.53†	0.59*	0.71**	0.69*	0.81**	0.58*	0.83**	0.85**	0.65†
Hind cannon length	0.65*	0.60*	0.79**	0.68**	0.86***	0.75**	0.67*	0.92***	0.81**	0.91***	0.79**	0.67†	0.64†

†P < 0.10 *P < 0.05 **P < 0.01 ***P < 0.001

Table 5. Correlations between wither height and all linear conformation traits at all investigated ages

Figure 1. Skin marker locations; 1. Wing of the atlas; 2. Proximal end of the scapular spine; 3. Greater tubercle of the humerus; 4. Lateral epicondyle of the humerus; 5. Lateral prominence of the distal radius; 6. Center of metacarpus; 7. Metacarpal tuberocity; 8. Distal end of the metacarpus; 9. Dorsal ridge of the ilium tuber coxae; 10. Greater trochanter of the femur; 11. Trochlear ridge of the femur; 12. Lateral malleolus of the tibia; 13. Metatarsal tuberocity; 14. Distal end of the metatarsus. (Adapted from Holmstrom et al., 1990)

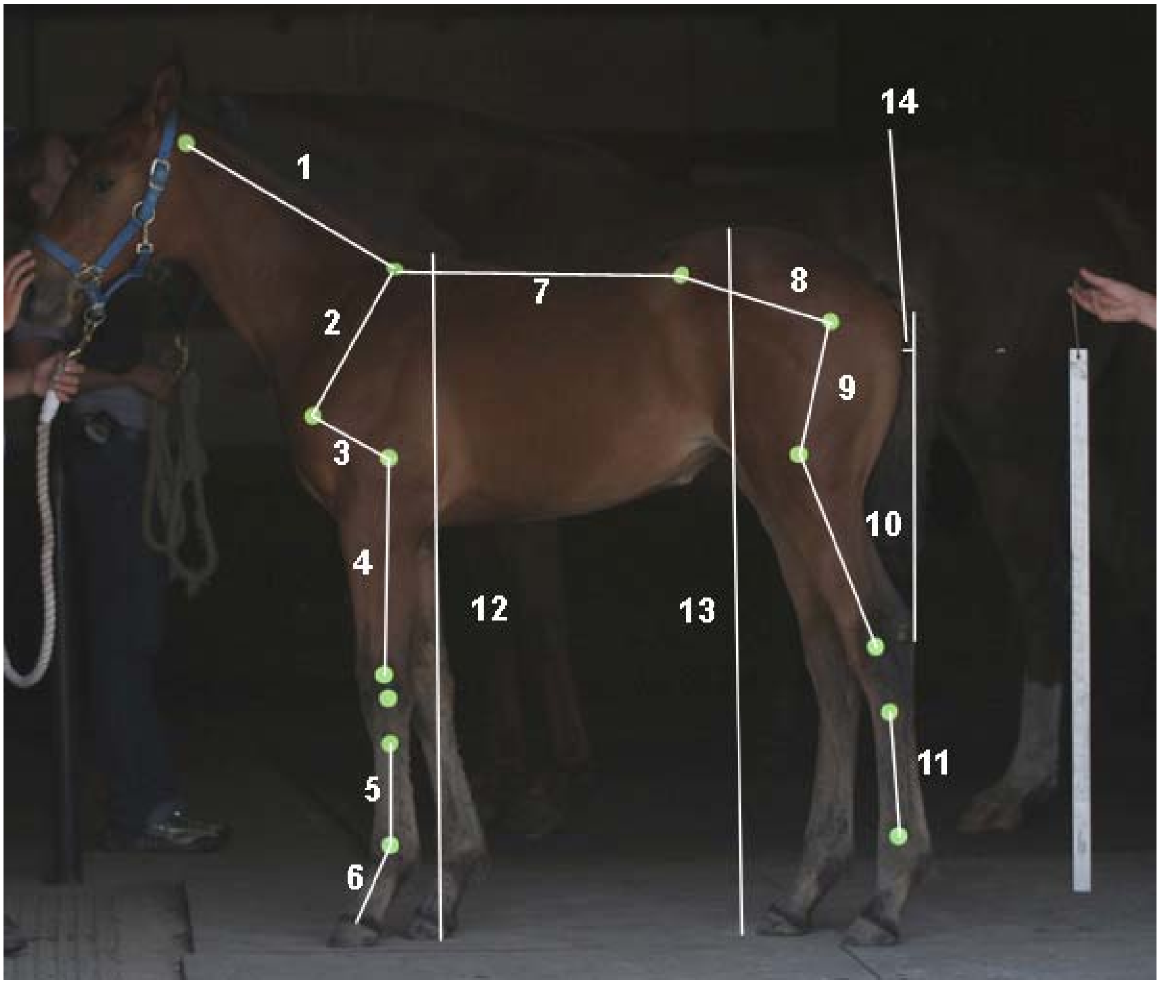


Figure 2. Length measurements; 1. Neck; 2. Scapula; 3. Humerus; 4. Radius; 5. Third metacarpus; 6. Front fetlock; 7. Back; 8. Ilium; 9. Femur; 10. Tibia; 11. Third metatarsus; 12. Wither height; 13. Hip height. 14. Distance out behind.

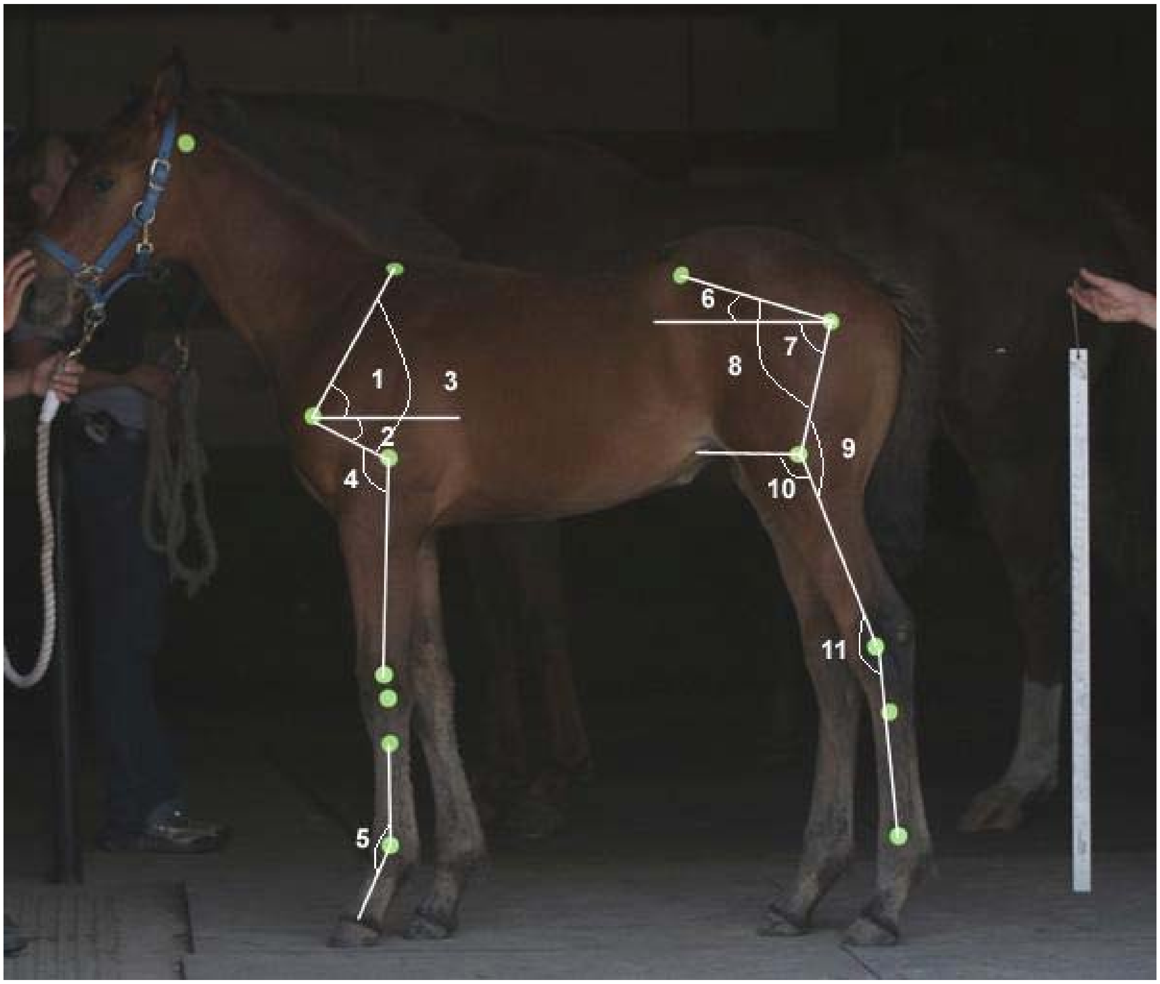


Figure 3. Angle Measurements; 1. Scapula; 2. Humerus; 3. Shoulder; 4. Elbow; 5. Front Fetlock; 6. Ilium; 7. Femur; 8. Hip; 9. Stifle; 10. Femur; 11. Hock

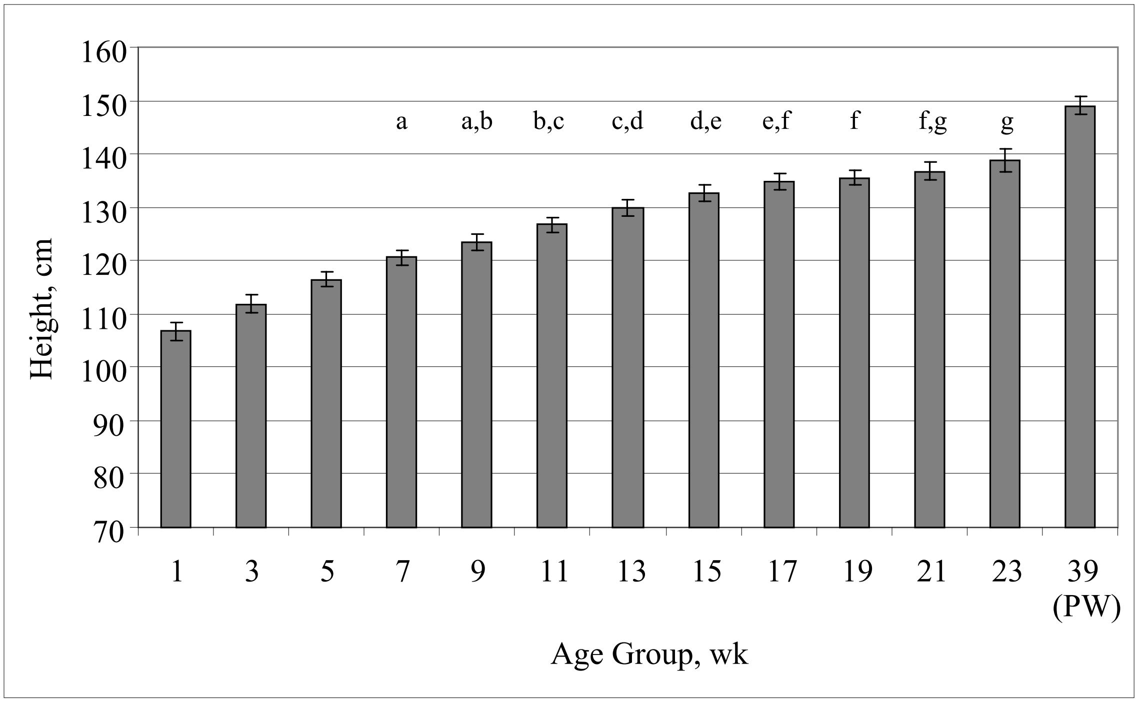


Figure 4. Mean (± SEM) wither height at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

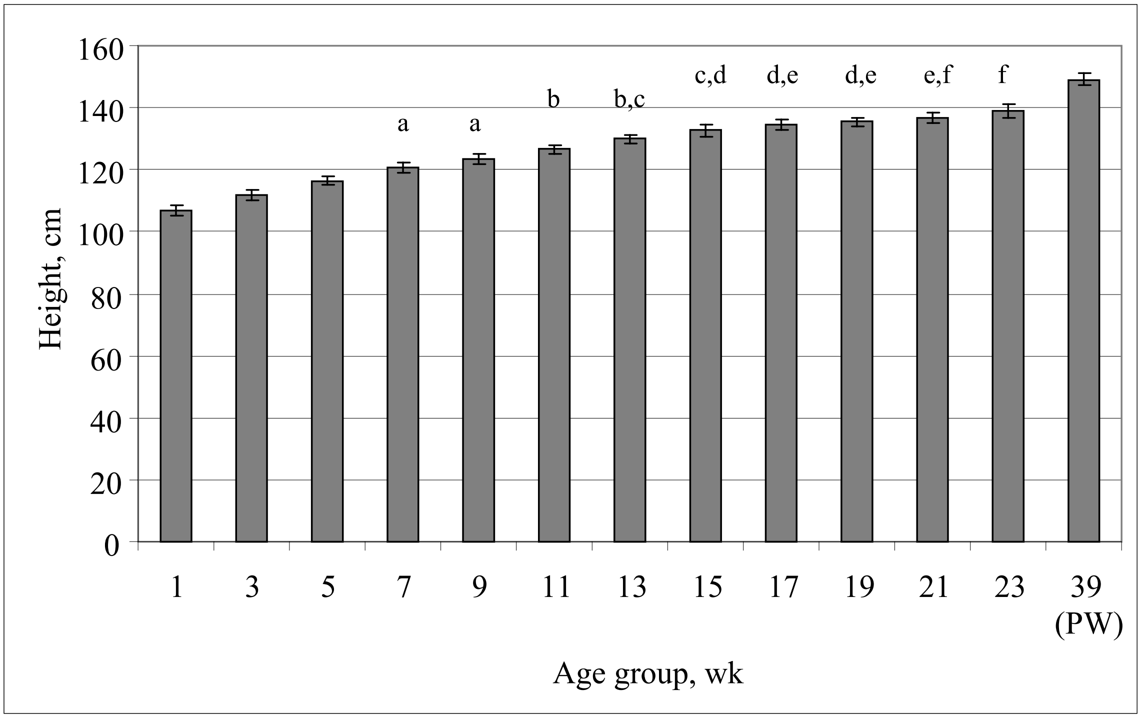


Figure 5. Mean (± SEM) hip height at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

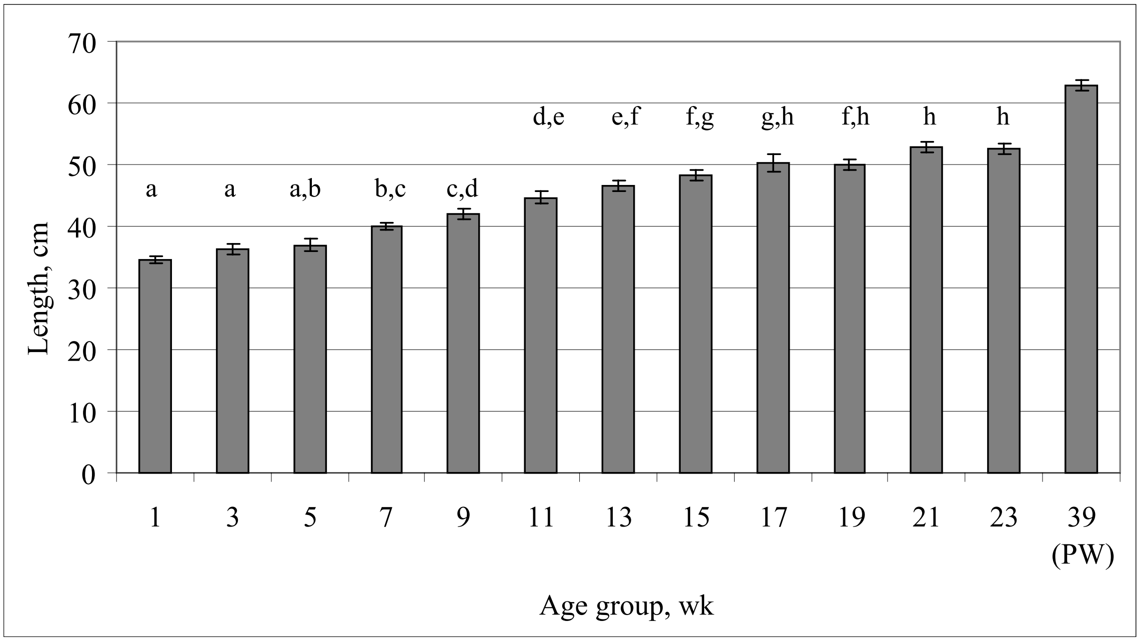


Figure 6. Mean (± SEM) neck length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

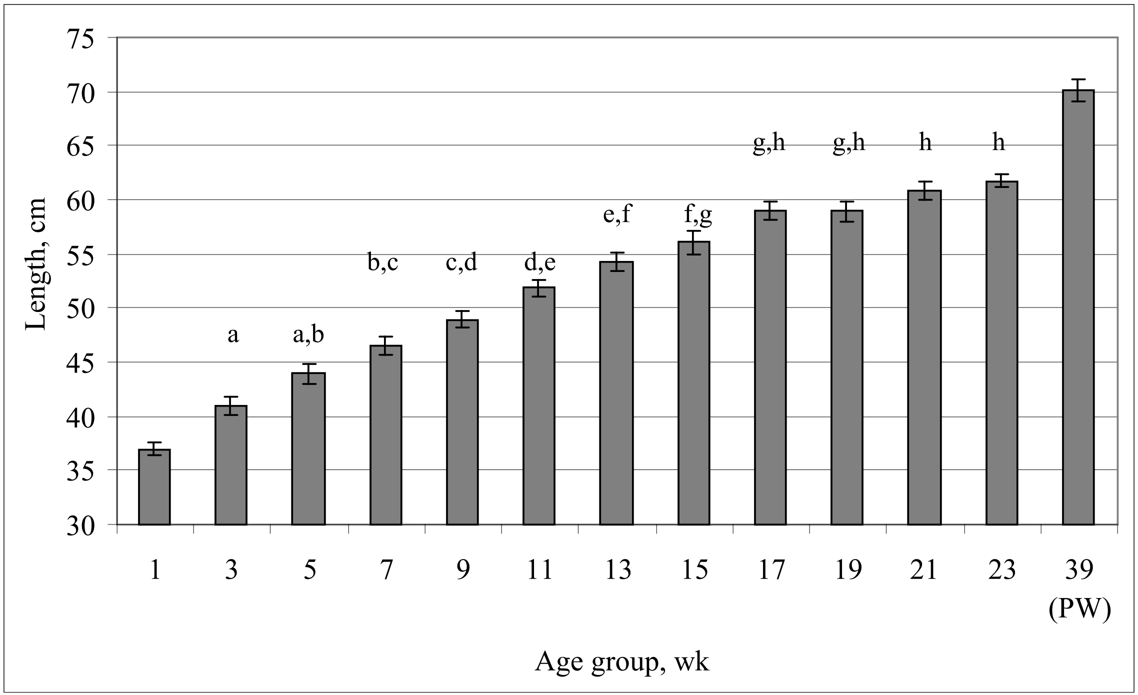


Figure 7. Mean (± SEM) back length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

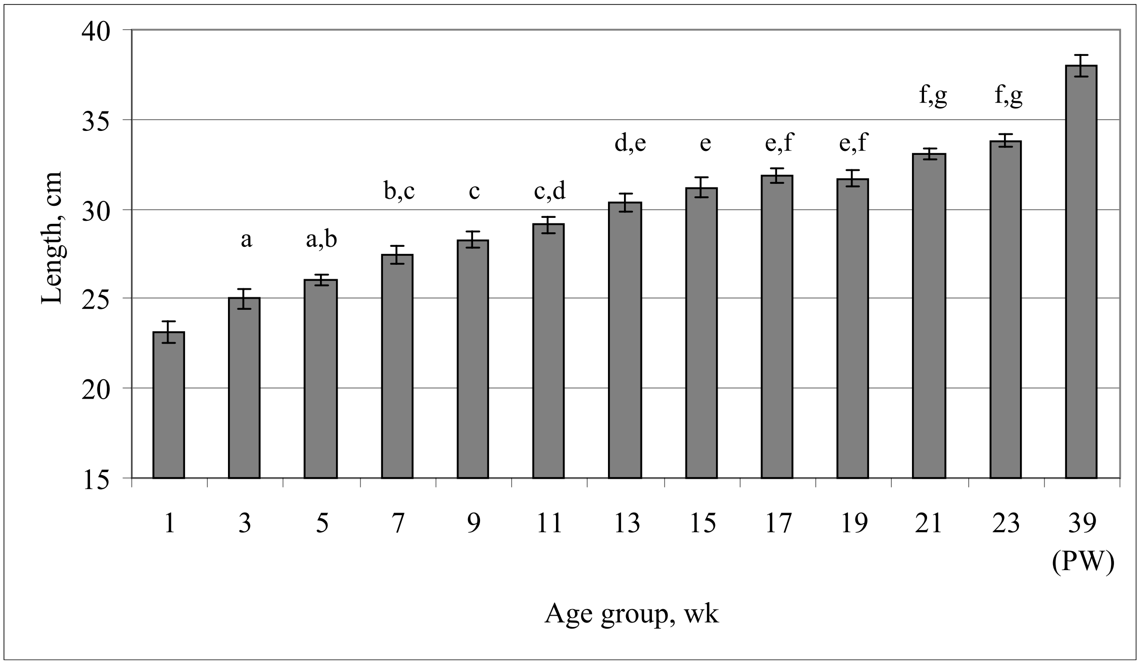


Figure 8. Mean (± SEM) scapula length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

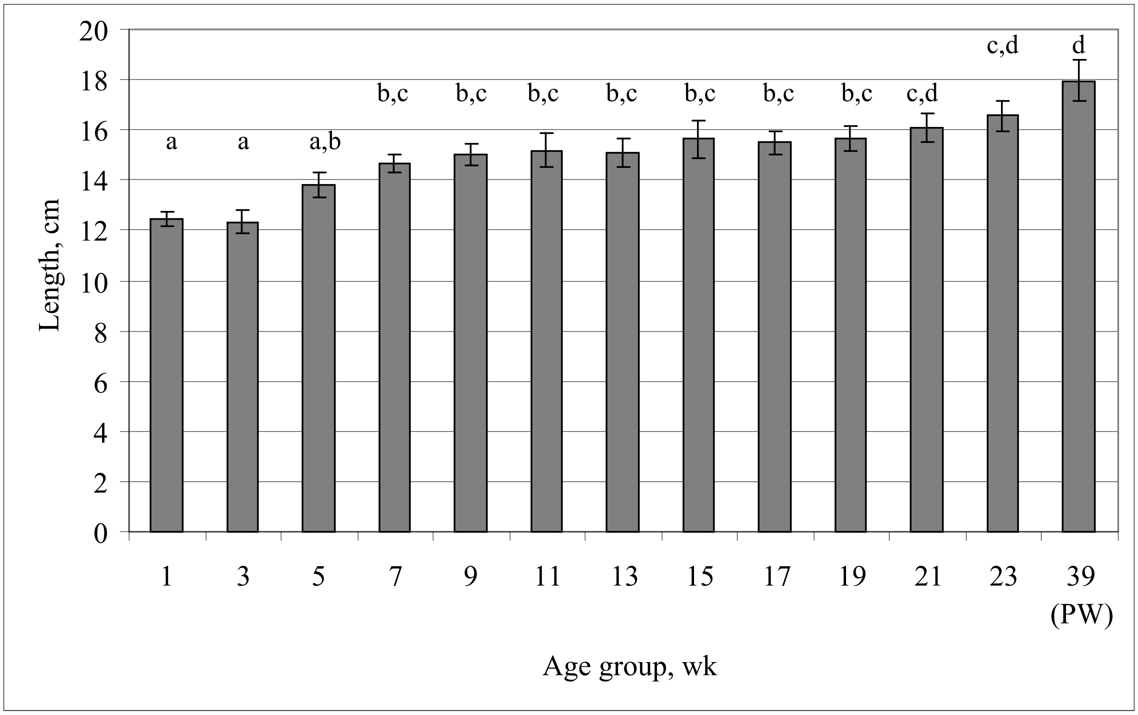


Figure 9. Mean (± SEM) humerus length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

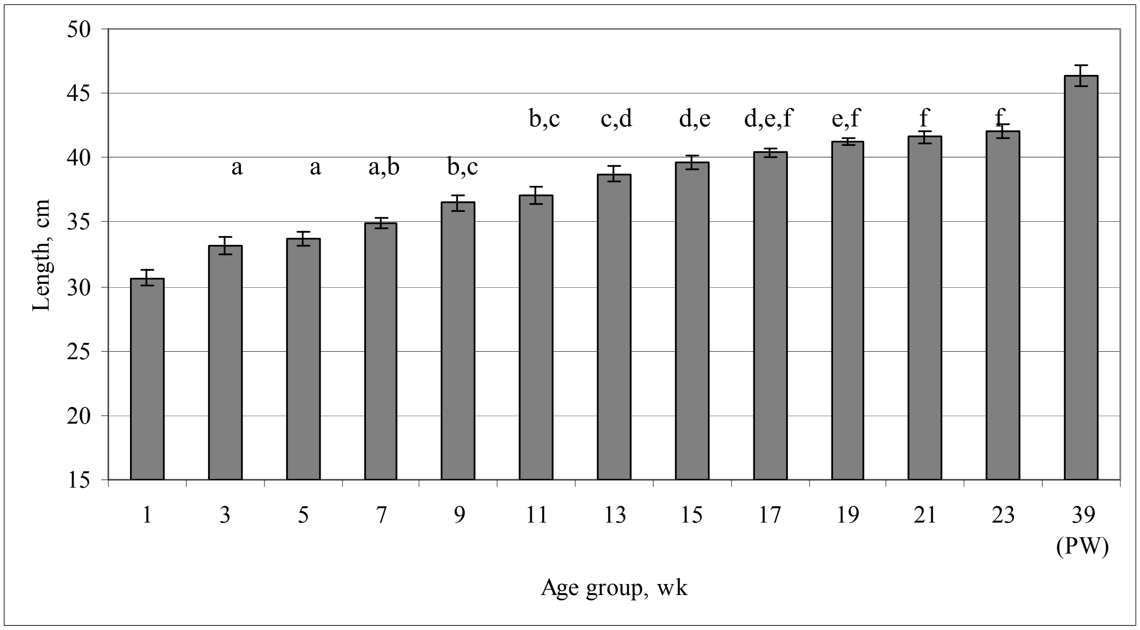


Figure 10. Mean (± SEM) radius length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

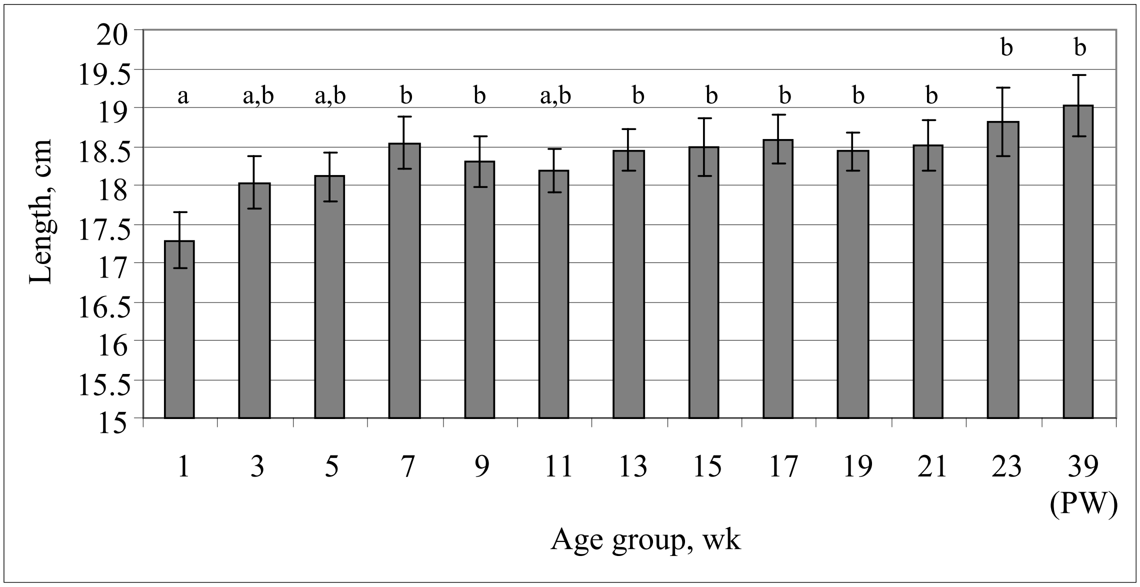


Figure 11. Mean (± SEM) third metacarpal length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

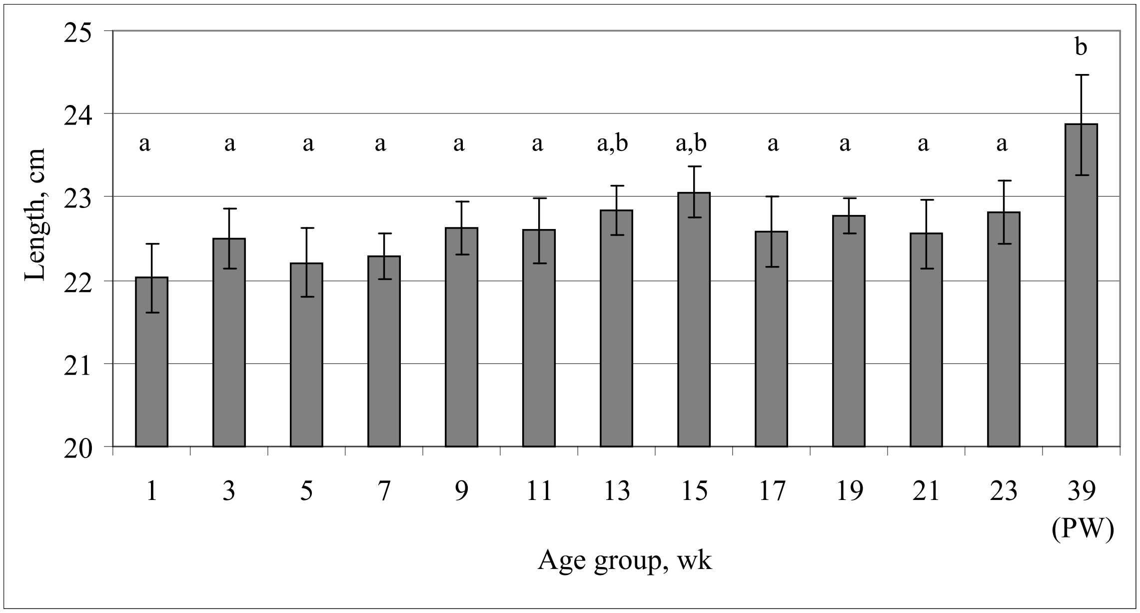


Figure 12. Mean (± SEM) third metatarsal length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

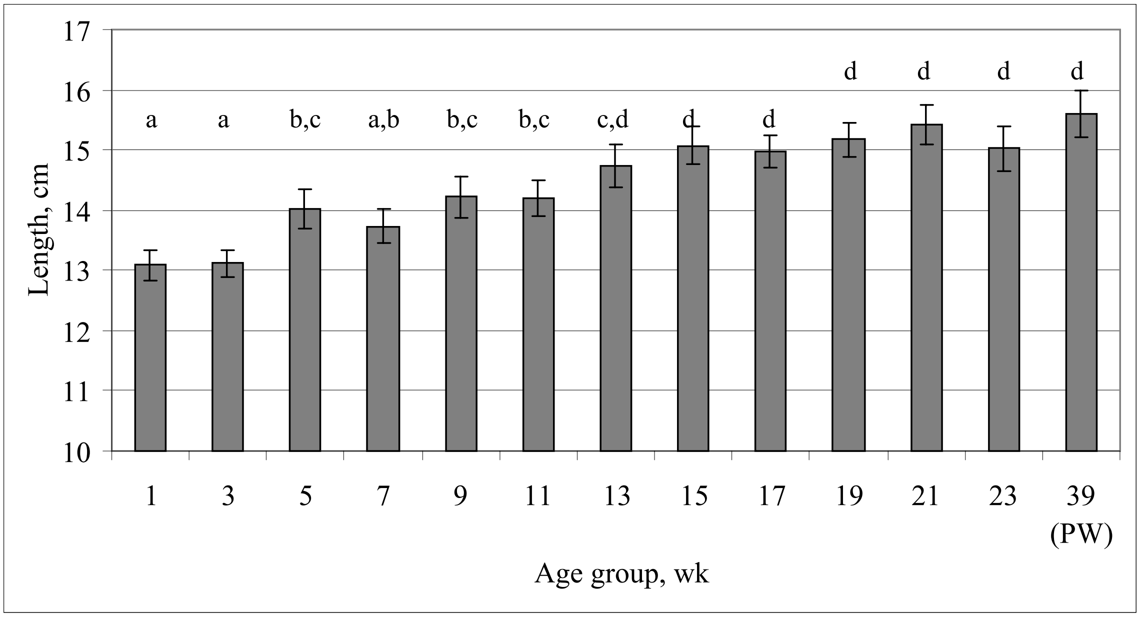


Figure 13. Mean (± SEM) front fetlock length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

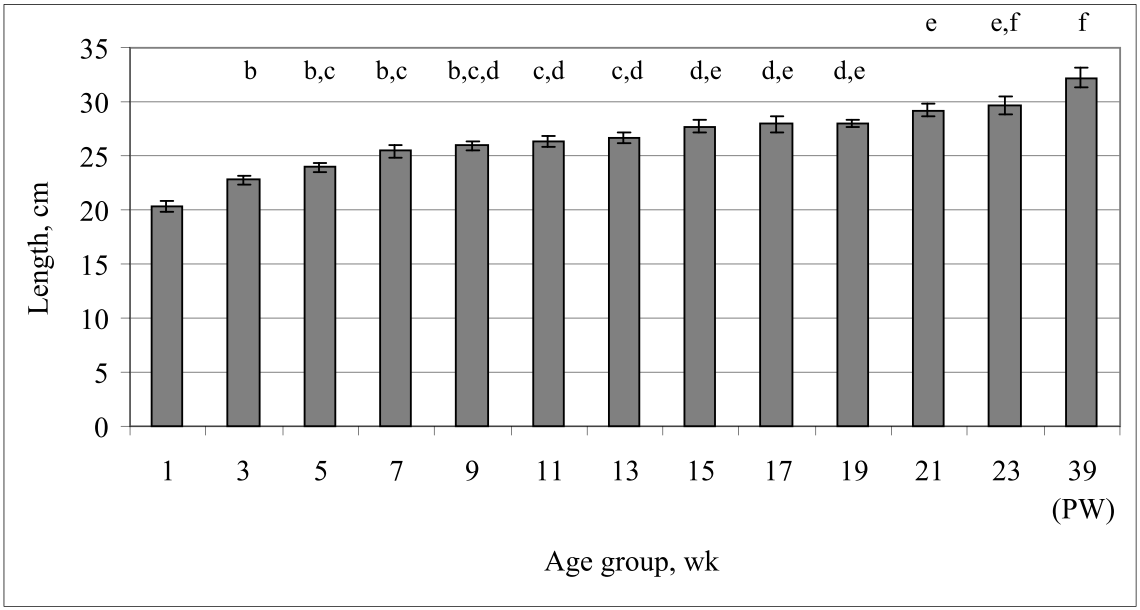


Figure 14. Mean (± SEM) ilium length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

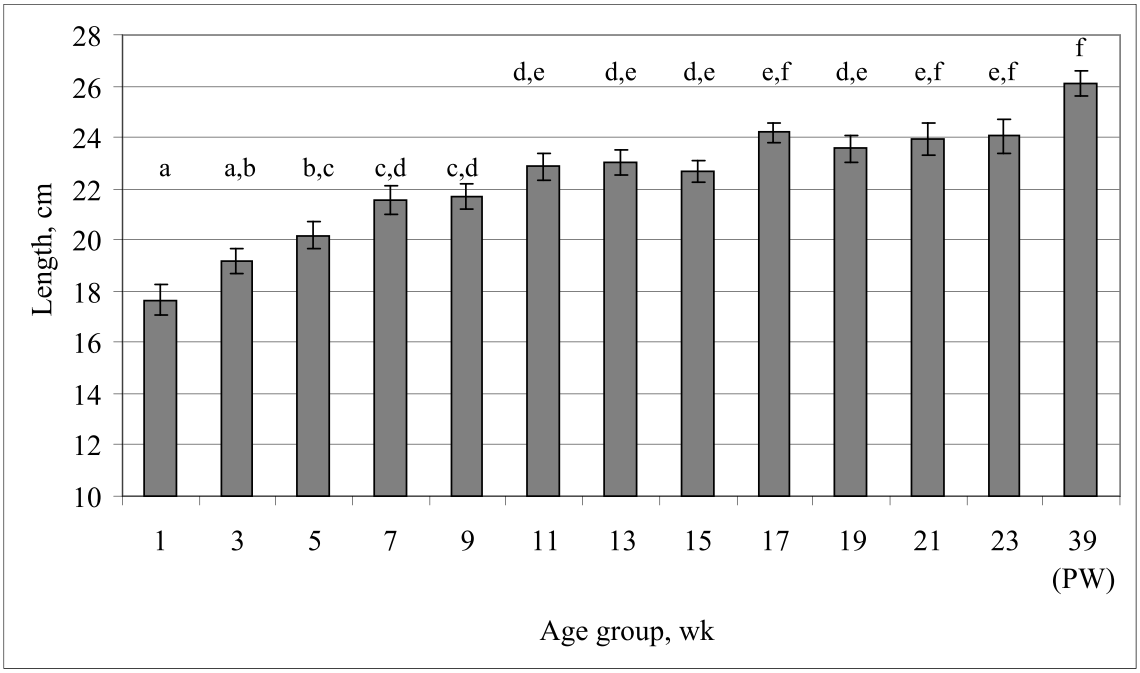


Figure 15. Mean (± SEM) femur length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

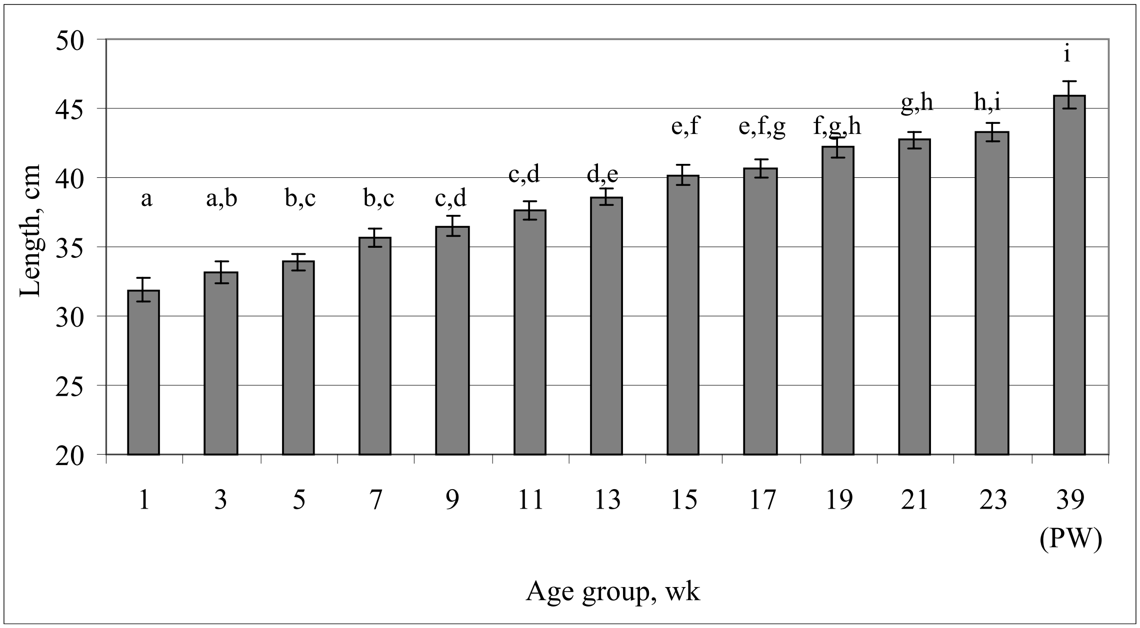


Figure 16. Mean (± SEM) tibia length at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

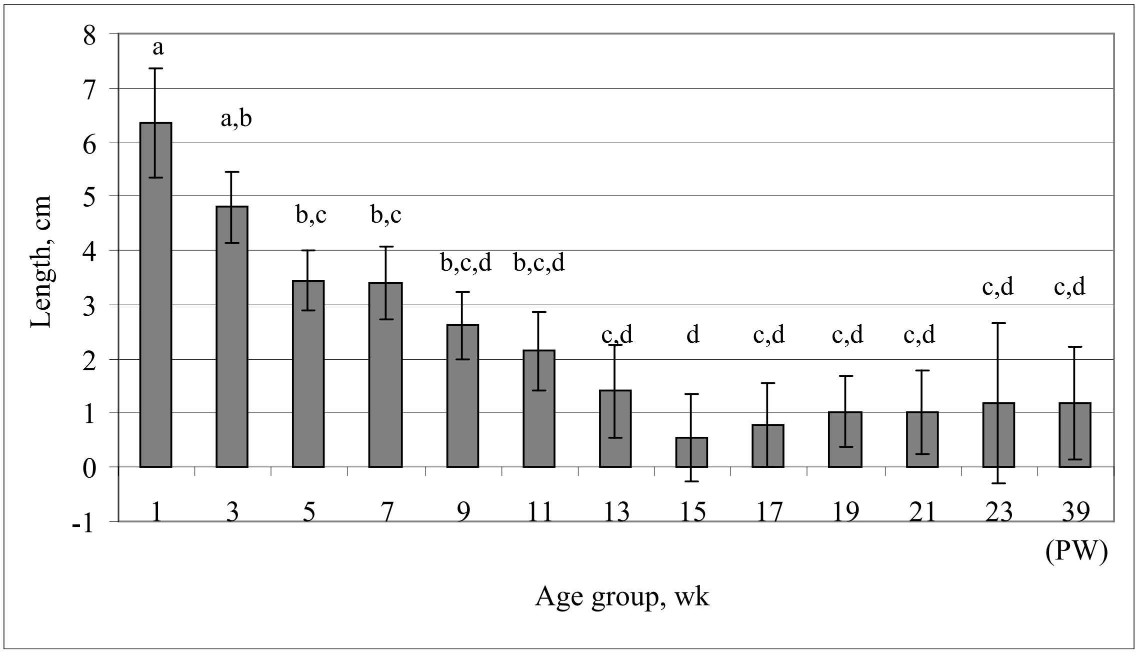


Figure 17. Mean (± SEM) distance out behind at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

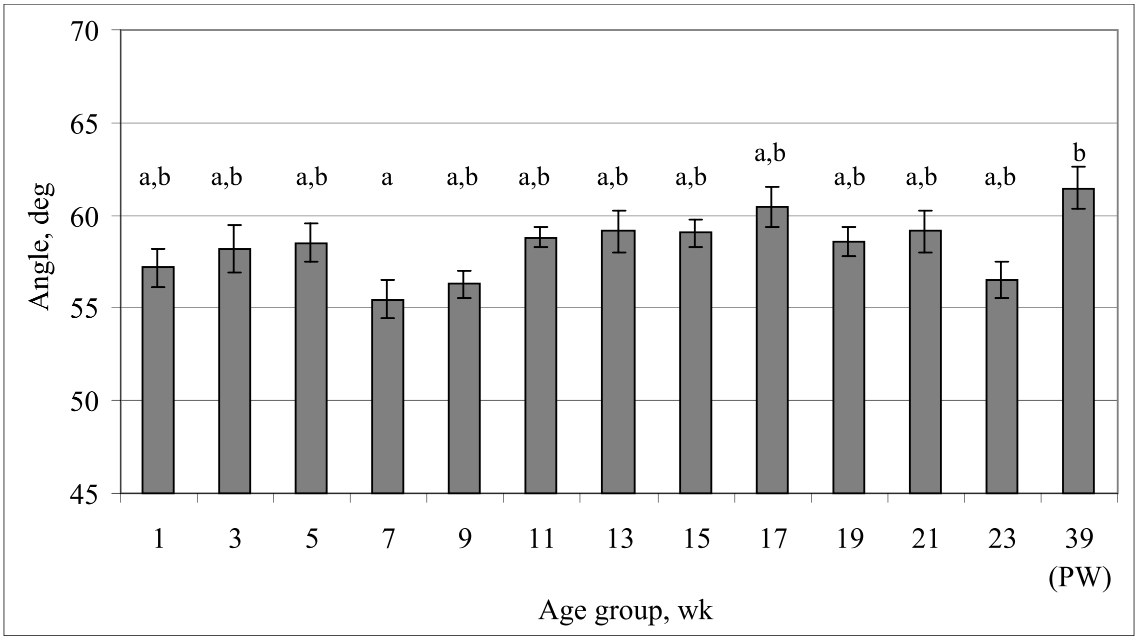


Figure 18. Mean (± SEM) scapula angle at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

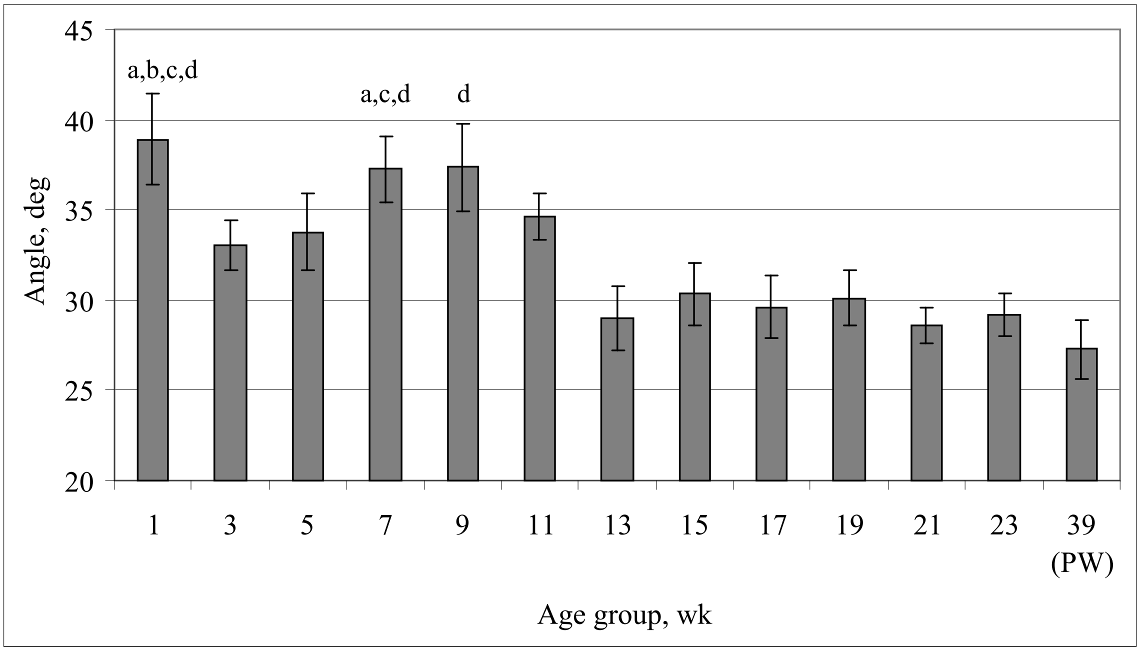


Figure 19. Mean (± SEM) humerus angle at all investigated ages from 1 wk to post-weaning (PW). a = differs from 13 wk ($P < 0.05$) b = differs from 17 wk ($P <0.05$) c = differs from 21 wk ($P <0.05$) d = differs from PW ($P < 0.05$). No other significant differences exist.

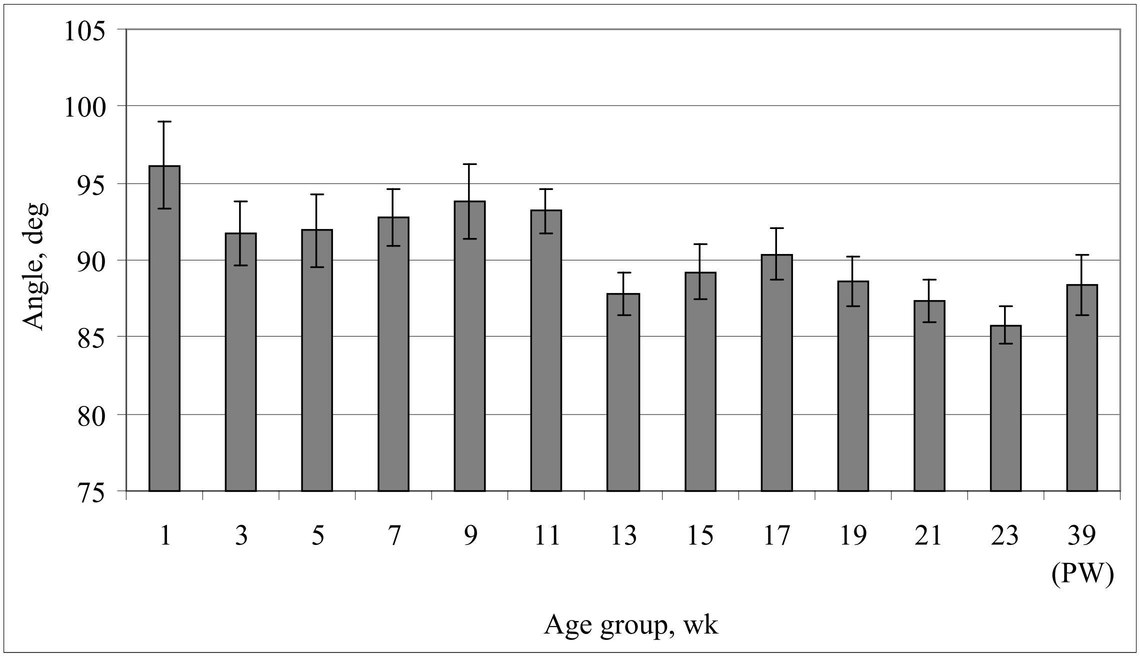


Figure 20. Mean (± SEM) shoulder angle at all investigated ages from 1 wk to post-weaning (PW). No significant differences exist between age groups ($P < 0.05$).

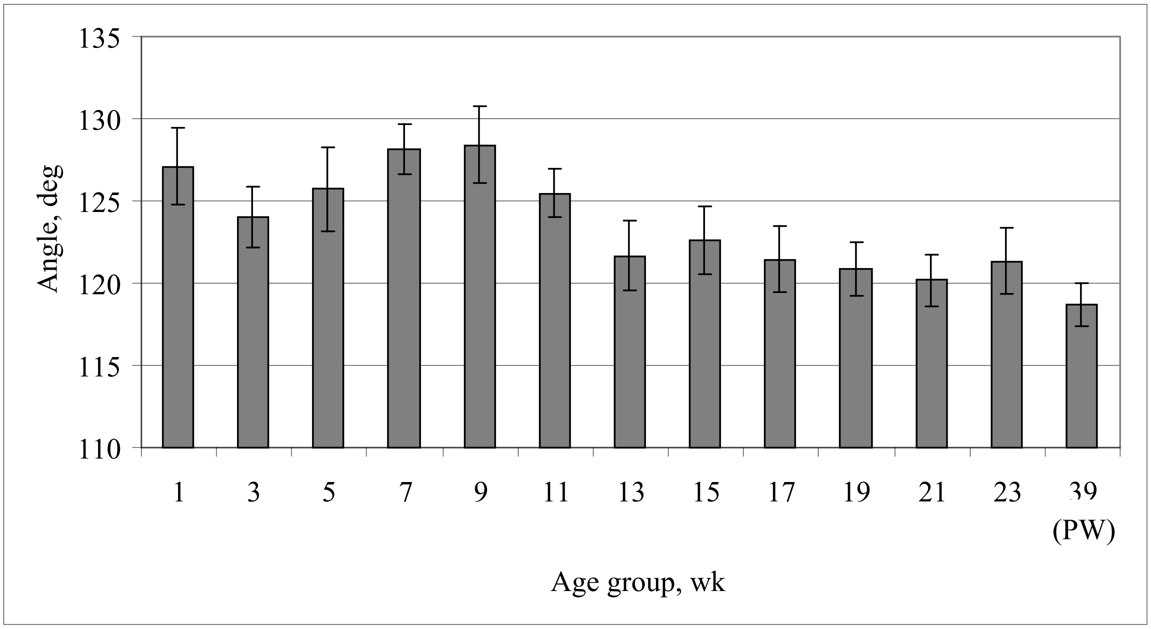


Figure 21. Mean (± SEM) elbow angle at all investigated ages from 1 wk to post-weaning (PW). No significant differences exist between age groups ($P < 0.05$).

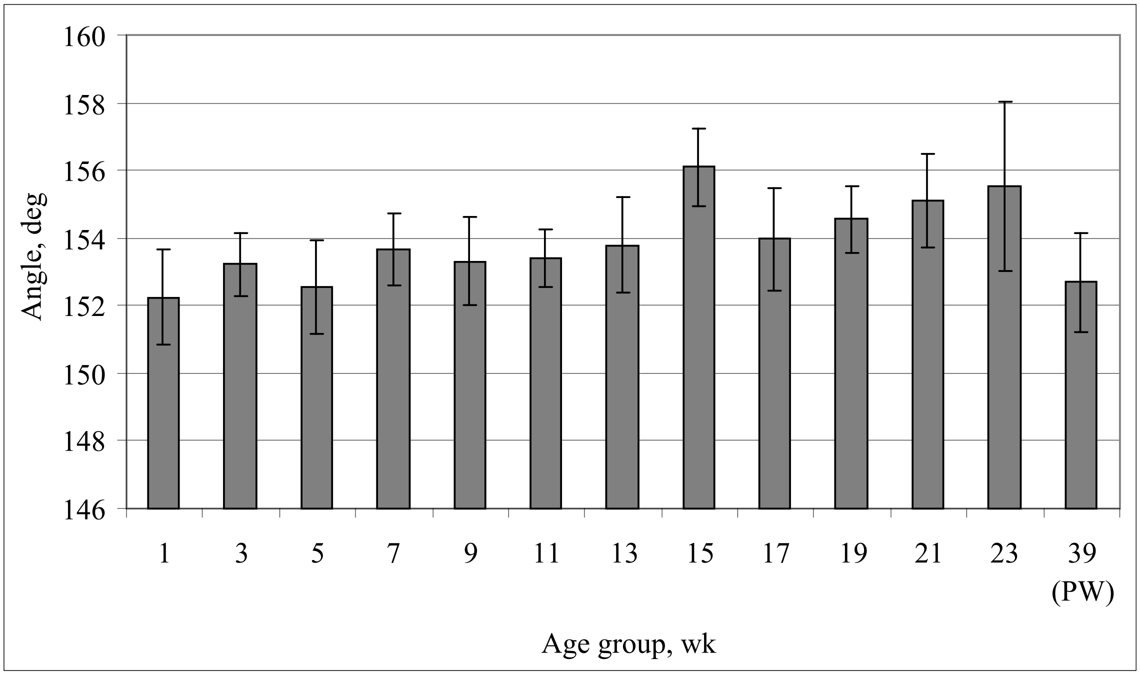


Figure 22. Mean (± SEM) fetlock angle at all investigated ages from 1 wk to post-weaning (PW). No significant differences exist between age groups ($P < 0.05$).

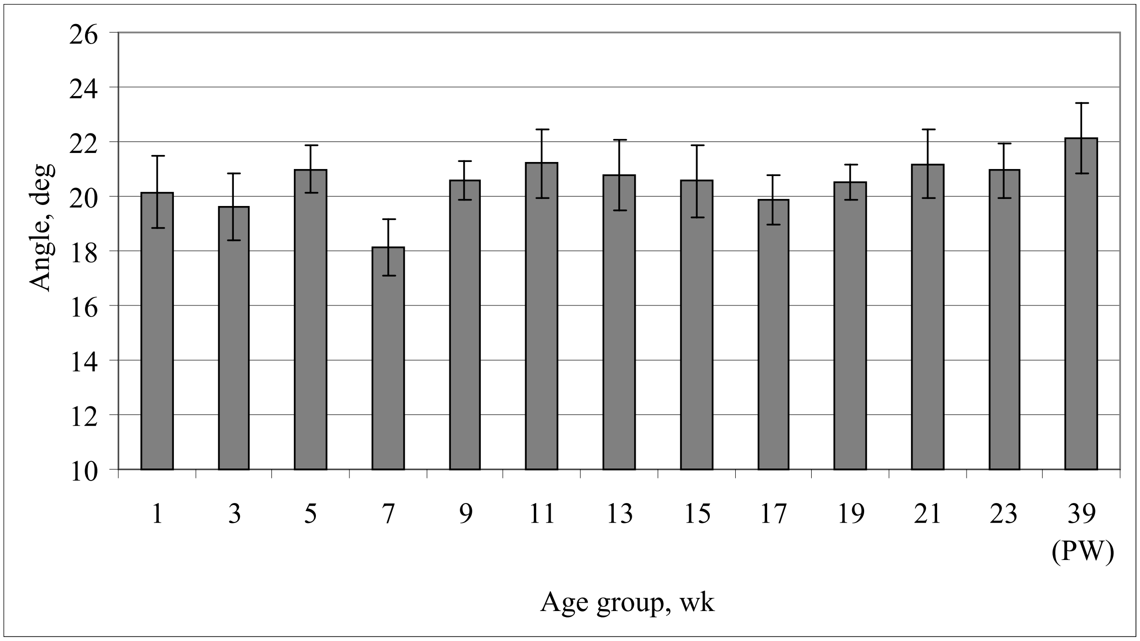


Figure 23. Mean (± SEM) ilium angle at all investigated ages from 1 wk to post-weaning (PW). No significant differences exist between age groups ($P < 0.05$).

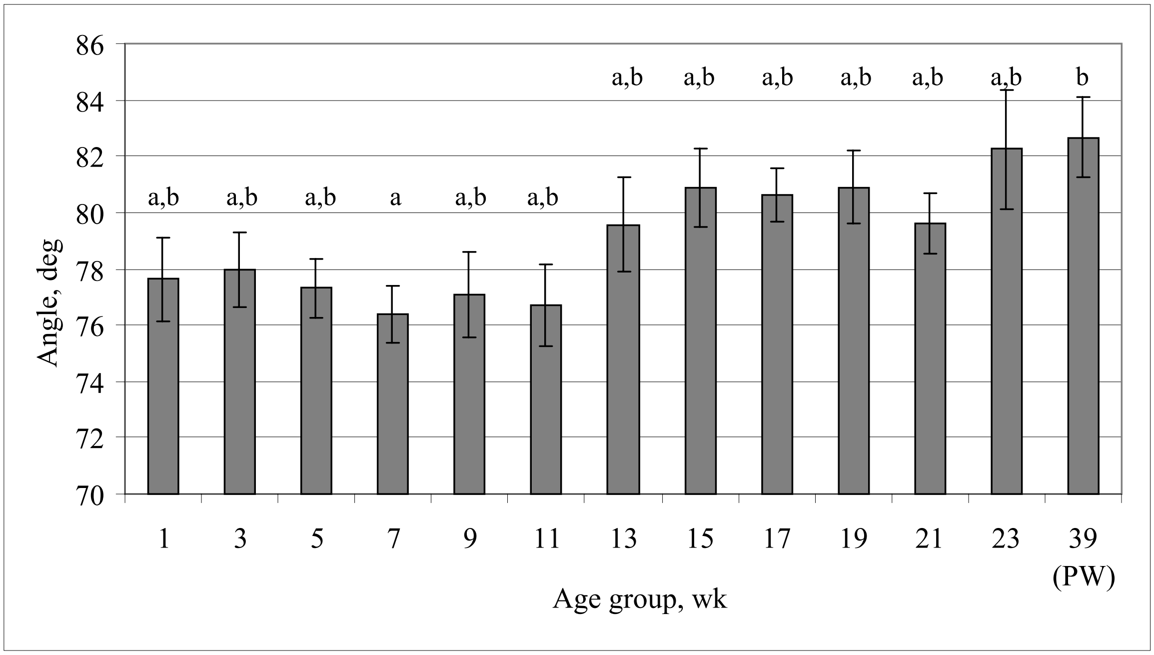


Figure 24. Mean (± SEM) femur angle at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

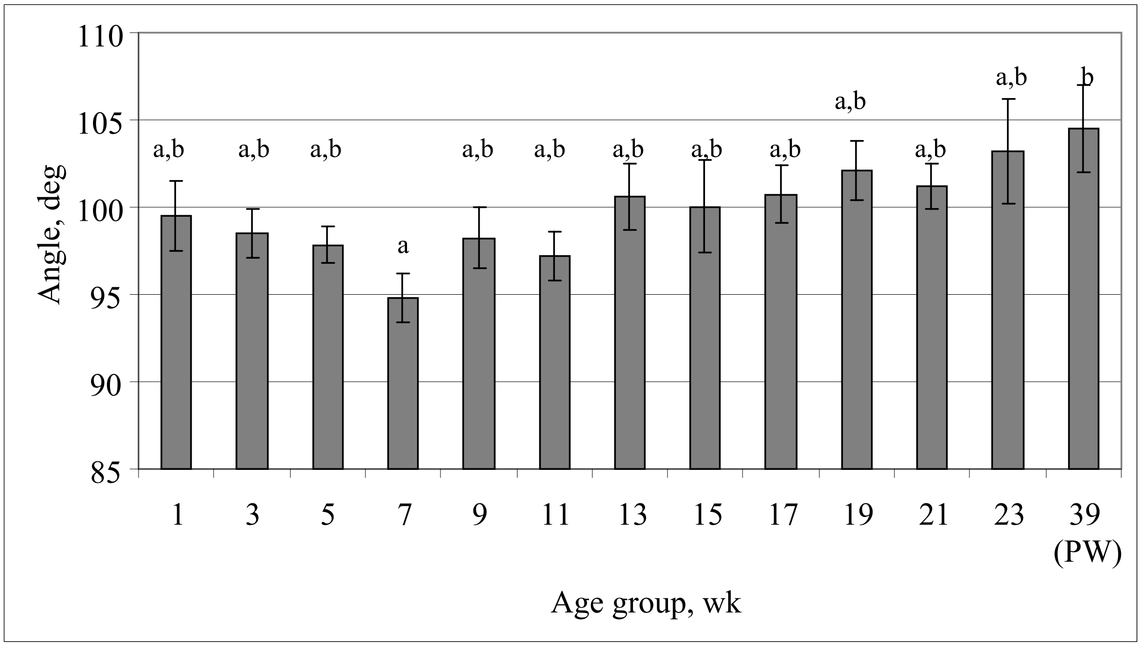


Figure 25. Mean (± SEM) hip angle at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

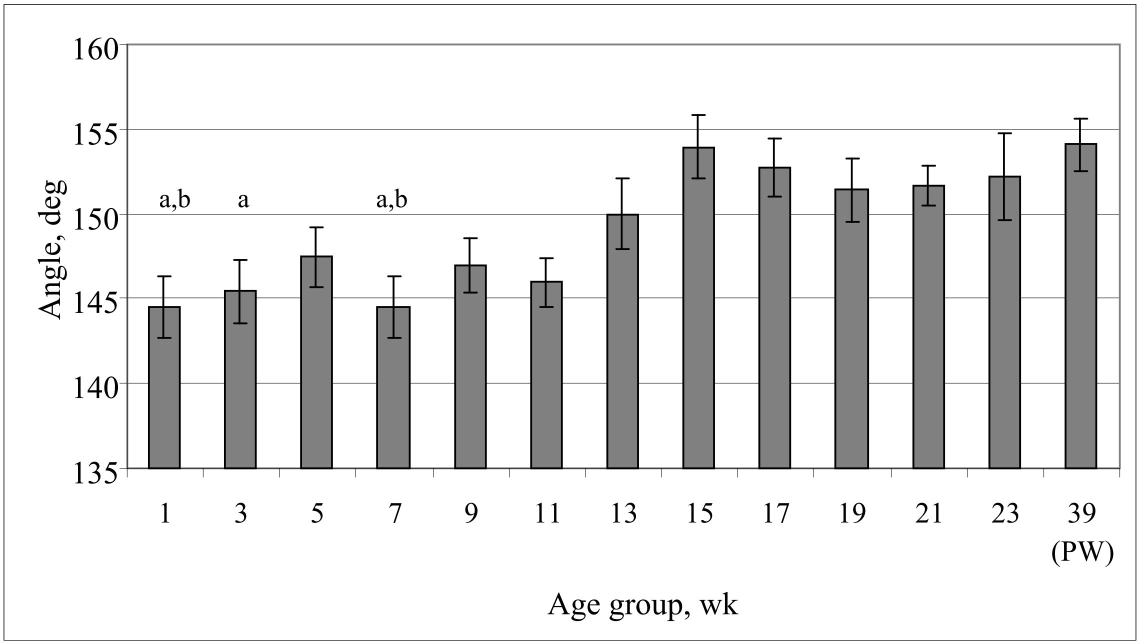


Figure 26. Mean (± SEM) stifle angle at all investigated ages from 1 wk to post-weaning (PW). a = differs from 15 wk ($P < 0.05$) b = differs from PW ($P < 0.05$).

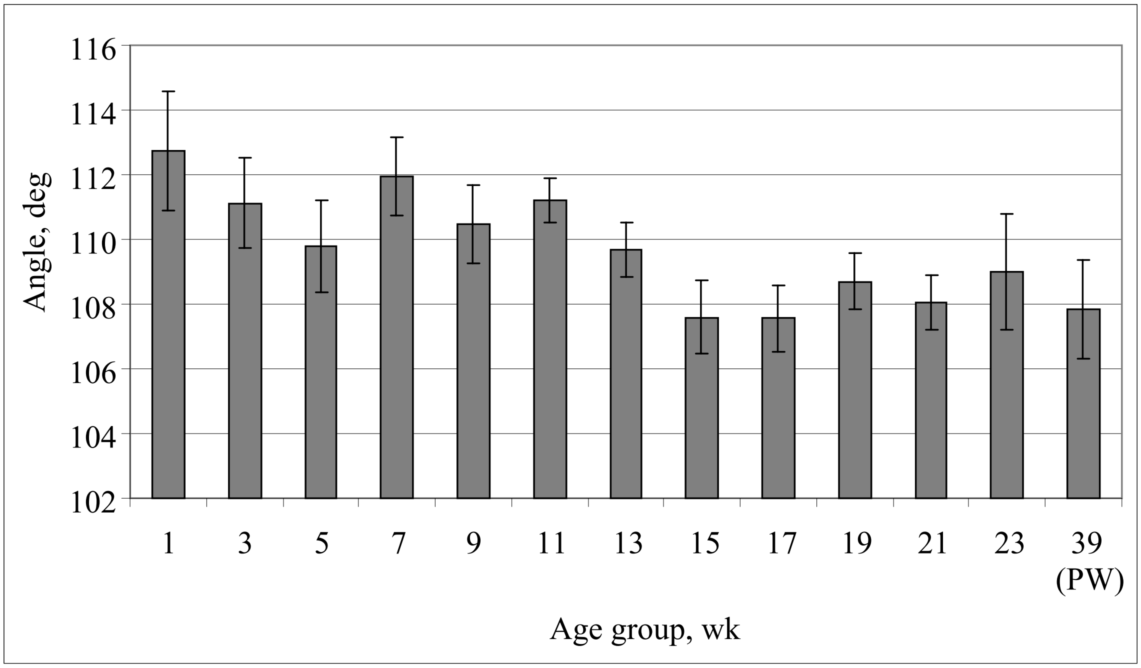


Figure 27. Mean (± SEM) tibia angle at all investigated ages from 1 wk to post-weaning (PW). No significant differences exist between age groups ($P < 0.05$).

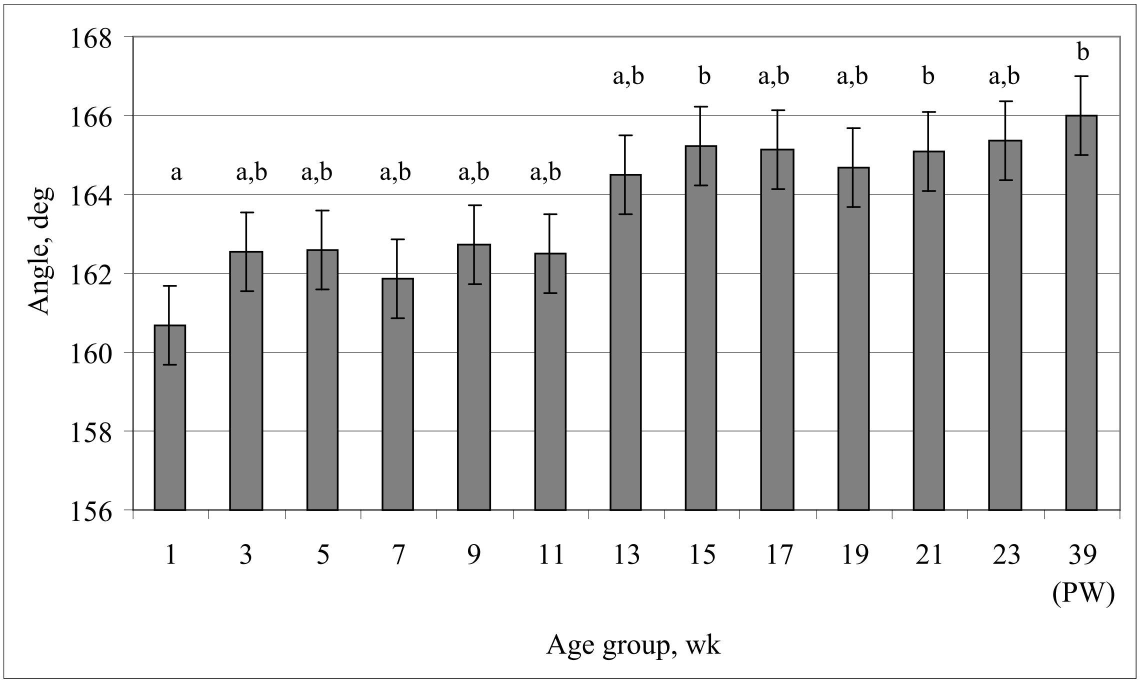


Figure 28. Mean (± SEM) hock angle at all investigated ages from 1 wk to post-weaning (PW). Bars with similar letters do not differ significantly ($P < 0.05$).

Figure 29. Foal displaying extremely camped out conformation. When standing with hind cannon bones perpendicular to the ground, the hindlimb stands far behind the most caudal point of the semitendinosus. This foal was not included in the study due to the severity of this condition.

CHAPTER IV

Linear and Temporal Walk Kinematics in Suckling and Weanling Warmblood Foals

S.F. Denham[1], W.B. Staniar[1], J.J. Dascanio[2], and R.K. Splan[1]

[1]Department of Animal and Poultry Sciences, Virginia Tech, Blacksburg, VA

[2]Large Animal Clinical Sciences, Virginia-Maryland Regional College of Veterinary Medicine, Blacksburg, VA

Abstract

Gait quality is an important selection criterion for warmblood sport horses. Therefore the gait of warmblood foals is often subjectively evaluated by breed registries at a young age. However, little work has been done to quantify kinematic changes that occur during the early growth of warmblood foals to understand how foal gait patterns change during postnatal development. The objective of this study was to quantify the linear and temporal walk pattern changes occurring in growing warmblood foals. Nine warmblood foals were videotaped at the walk at 3, 11 and 21 wk of age. A final recording of all foals was made post-weaning when foals averaged 39 wk of age. Variables were standardized to percentage of stride length or duration. Repeated measures analysis was used to compare trait means between age groups. Stride length and duration increased significantly between all age groups. Step length and limb protraction and retraction durations were not different between any age group. Timing between lateral and diagonal footfalls remained significantly different at all ages. Neither lateral nor diagonal timing variables changed with age. Over-stride decreased significantly until 21 wk. In adult horses, the walk is described as an even 4-beat symmetrical gait. However, significant differences between lateral and diagonal timing at all studied ages indicates that the development of an even 4-beat walk is incomplete by 39 wk. Changes in kinematics during growth should be considered when evaluating the walk quality of immature warmbloods.

Introduction

Warmblood gait quality is examined at a young age and is used to evaluate the animal's monetary value and adult performance potential. Mare and foal inspections are conducted by individual breed registries to evaluate and score breeding stock and offspring (Swedish Warmblood Association of North America, 2006; American Hanoverian Society, 2007). Inspection results are often heavily weighted by industry as an indicator of warmblood foal quality and athletic potential (Wallin et al., 1995). However, these scores reflect the presentation of the animal on a single day and are highly subjective. There is also a shortage of knowledge of how foal gait pattern relates to adult performance success. Thus, these scores may not accurately represent an animal's athletic potential.

Linear and dynamic adjustments of foal trot kinematics have been used to accurately predict adult values (Back et al., 1995). However, the quantitative gait pattern changes during early growth in the young foal have not been thoroughly investigated. This study characterizes changes in linear and temporal walk patterns occurring during the first ten months of growth.

Materials and Methods

Animals

Nine warmblood foals (2 colts and 7 fillies) born between March 6 and May 16, 2006 were used in this study. All foals were born and raised at the Virginia Tech Smithfield Horse Center in Blacksburg, Virginia. Mares and foals were group housed on native grass pastures and supplemented with a balanced ration concentrate to maintain mare body condition score (BCS) of 6-7 pre-weaning and a foal BCS of 5-6 post-weaning.

Video Recording

Video recordings were made at 3, 11 and 21 wk of age pre-weaning. A single post-weaning recording was made in January, 2007. Average foal age for the January recording was 39 wk. During video recording sessions, mares and foals were led over a level concrete surface covered with 13 mm hard rubber matting. Speed was controlled by a uniform handler maintaining a steady pace via metronome set to 88 beats per min, as this rate matched the comfortable, normal walking pace of the handler. A 60Hz digital video recorder in a consistent location was used for all video capture. All video was stored on digital tapes until transferred to computer hard drive for analysis.

Video Analysis

SIMI Motion video analysis software was used to for all video analysis (Simi Reality Motion Systems gmbh, 2004). Measurements taken included stride length, duration, speed, limb stance, duration of protraction and retraction, time between lateral and diagonal footfalls, step length, distance between diagonal limbs during stance and over-stride. All distances were measured from heel strike locations.

Stride length and duration were measured as the distance or time between left hind limb heel strikes. Speed was calculated by dividing stride length by stride duration. Limb stance was the time between heel strike and toe off. The timing of protraction and retraction during stance were calculated using heel strike, when the cannon bone became perpendicular to the ground and toe off. Left front step length was measured as the distance between the right fore heel and left fore heel at the time the left heel struck the ground. Right fore and right and left hind step lengths were calculated similarly. The distance between diagonal pairs was measured between ipsilateral heel strike locations while both limbs were in the stance phase. Over-stride was the distance by which the heel strike of the hind hoof preceded the heel strike of the contralateral forehoof. Distance and time variables were standardized to percentage of stride length or stride duration.

Statistical Analysis

All statistical analysis was done using SAS/STAT software (SAS Institute, 2002-2004). Variable means from three clean strides per recording session were used. Age groups investigated included 3 wk (mean = 19 d, n = 9), 11 wk (mean = 73 d, n = 9), 21 wk (mean = 144 d, n = 9), and post-weaning (mean = 271 d, n = 8). Repeated measures analysis was used to compare trait means at 3, 11, and 21 wk of age and post-weaning. Speed was included as a covariate in the model to account for possible differences. Significance is reported at the $P < 0.05$ level.

Results

Mean temporal kinematic variables within age groups are listed in Table 1. Linear variables are listed by age in Table 2. No significant differences were detected between right and left over-strides at any age. Therefore, values were collapsed into one variable.

Distance between diagonal pairs did not differ between limb pairs and thus were also collapsed into one variable.

As expected, stride duration increased with age ($P \leq 0.02$). Stride length increased from 3 to 11 wk ($P = 0.0002$), from 11 to 21 wk ($P = 0.06$) and 21 wk to post-weaning ($P = 0.0076$). No significant differences between step lengths existed in any limb or age group. However, over-stride decreased significantly from 3 to 11 wk ($P = 0.001$) and 11 to 21 wk ($P = 0.02$). The distance between diagonal limb pairs during stance phase decreased significantly from 3 to 11 wk ($P = 0.0001$) and 11 to 21 ($P = 0.0005$) wk, but did not change between 21 wk and post-weaning. Changes in lateral and diagonal footfall timing were not significant during the investigated ages. Lateral and diagonal timing were significantly different from each other at all ages.

Discussion

Increases in stride length and duration are most likely attributable to increasing back length and height at the withers. Positive correlations between wither height and trot stride length and duration have been previously reported in Andalusian foals (Cano et al., 2001). This relationship is also reported in adult Andalusian horses (Galisteo et al., 1998) However, many other investigations into the relationship between wither height and stride length in both foals and adult horses report no correlation between these traits (Leach and Cymbaluk, 1986; Back et al., 1994b, 2002). The small number of foals in the current study, and the small range of wither heights at each age, did not provide enough statistical power to investigate the relationships between these traits. This study serves as a pilot for future investigation of changes during growth and correlations between traits in larger populations.

While no previous reports of the relationship between back length and stride length at the walk are available, Quarter Horse and Thoroughbred foals between 6 and 8 mo displayed a significant relationship between back length and stride length at the trot (Leach and Cymbaluk, 1986). It is logical to assume that as the standing distance between front and hind limbs increases, so does total ground covered. Step-wise linear regression also revealed that morphometric influences on stride length are complex, and involve both linear and angular conformation measurements (Leach and Cymbaluk, 1986). However, the small number of horses utilized in this study precluded the usefulness of investigation of relationships between conformation and gait.

Inconsistent statistical significance of increasing stance duration is likely due to the small number of foals included in the study. In Shetland ponies evaluated at the trot, stance duration increased between 4 and 24 mo (Back et al., 2002). Dutch warmblood foals also displayed increased stance duration as percentage of stride with age at the trot (Back et al., 1994b).

Figure 1 displays the relationship between changing over-stride and distance between diagonal limbs. As step lengths did not change, it is likely that changes in over-stride and distance between diagonal limbs are due to changing body proportions during growth. Over the investigated ages, percentage of back length growth was greater than any limb trait. Therefore, the increasing distance between front and hind limbs is likely a cause for changing over-stride and distance between diagonal limbs.

The rhythm of the walk is an important defining feature of this gait. The walk is described as a four-beat symmetrical gait with no period of suspension and long overlap times between limb stance phases (Hildebrand, 1965). A regular, even 4-beat "pure" walk must have equal timing between lateral and diagonal footfalls (Federation Equestre Internationale, 2006). Comparisons of the time between lateral and diagonal footfalls can be used to evaluate regularity of the walk (Hodson et al., 1999). One interesting anecdotal observation of the walk in foals is the appearance of increased gait laterality at younger ages. The difference between lateral and diagonal footfall timing did decrease over the ages studied, however after Sidak adjustments this difference was not significant (Fig 2). The lack of statistical significance is likely due to the small number of foals in this study. However, even at the post-weaning measurement age, a difference between lateral and diagonal timing still existed. Therefore, while older foals do utilize a more even rhythm at the walk than at younger ages; the development of a "pure" four-beat gait is not complete by 39 wk (~10 mo).

In dressage, a sport dominated by warmblood breeds, the purity of the walk is an important judging criterion (Barrey et al., 2002; Federation Equestre Internationale, 2006). Therefore walk quality is an important consideration for trainers and owners when selecting young warmbloods for this sport. Quantification of the walk in adult horses confirm that a symmetrical gait is eventually developed (Clayton, 1995). Yet the development of a pure 4-beat walk appears to be incomplete by 10 mo of age. When young foals are evaluated as performance animals, investigators should consider that the walk symmetry will likely improve with age. However, laterality of the walk can also be genetic (Barrey et al., 2002) and the walk quality of both sire and dam may influence rather a pure walk is actually developed in adulthood. Further investigation of the walk pattern at later ages during growth is necessary to identify when the development of the walk should be completed in those horses not genetically predisposed to an uneven walk rhythm.

Gait quality is highly valued as a predictor of performance ability. The accurate identification of animals with the top potential at an earlier age is economically advantageous. Less money is lost due to training and care of animals not capable of top performance. Kinematic variables have been shown to correlate well with subjective gait quality scores given by experienced warmblood evaluators (Back et al., 1994a). Superior gait quality can therefore be detected through kinematic research. Understanding how kinematics change during growth will allow better prediction of gait quality in adult warmbloods and aid in the earlier selection of those animals most capable of becoming top athletic performers. While the ultimate success of a horse is dependant on a multitude of environmental factors, breeding and selecting more inherently capable animals is an important first step in the continued development of more successful equine athletes.

	Age Groups							
	3 wk		11 wk		21 wk		39 wk (PW)	
Trait (unit)	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Stride duration (s)	1.15^{a}	0.03	1.24^{b}	0.03	1.26^{c}	0.03	1.28^{d}	0.03
Speed (m/s)	0.84^{a}	0.02	0.84^{a}	0.01	0.88^{b}	0.02	0.95^{b}	0.03
L Hind Stance Duration (%)	$0.58^{a,b}$	0.01	0.57^{a}	0.01	0.61^{b}	0.01	$0.61^{a,b}$	0.01
L Fore Stance Duration (%)	0.60^{a}	0.01	0.61^{a}	0.01	0.63^{a}	0.01	0.63^{a}	0.01
R Hind Stance Duration (%)	0.64^{a}	0.00	0.64^{a}	0.00	0.65^{a}	0.01	0.65^{a}	0.01
R Fore Stance Duration (%)	0.63^{a}	0.00	$0.64^{a,b}$	0.00	0.66^{b}	0.01	$0.65^{a,b}$	0.01
Time Between Lateral Footfalls (%)	0.17^{a}	0.01	0.17^{a}	0.01	0.19^{a}	0.00	0.21^{a}	0.01
Time Between Diagonal Footfalls (%)	0.29^{a}	0.01	0.28^{a}	0.00	0.27^{a}	0.01	0.27^{a}	0.01
L Fore Protraction Duration (%)	0.21^{a}	0.01	0.20^{a}	0.01	0.22^{a}	0.01	0.20^{a}	0.00
L Hind Protraction Duration (%)	0.27^{a}	0.01	0.26^{a}	0.01	0.29^{a}	0.01	0.28^{a}	0.01
L Fore Retraction Duration (%)	0.39^{a}	0.01	0.41^{a}	0.01	0.41^{a}	0.01	0.43^{a}	0.01
L Hind Retraction Duration (%)	0.31^{a}	0.01	0.31^{a}	0.01	0.31^{a}	0.01	0.32^{a}	0.01

Within a row, means without a common superscript letter differ ($P < 0.05$)

Table 1. Temporal kinematic variables at all investigated ages from 3 wk to post-weaning (PW). L = Left; R = Right.

	Age Groups							
	3 wk		11 wk		21 wk		39 wk (PW)	
Trait (Unit)	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Stride length (m)	0.96^{a}	0.03	1.04^{b}	0.02	1.10^{b}	0.02	1.21^{c}	0.02
L Fore Step Length (%)	0.50^{a}	0.01	0.50^{a}	0.00	0.50^{a}	0.00	0.50^{a}	0.01
R Hind Step Length (%)	0.51^{a}	0.01	0.50^{a}	0.01	0.51^{a}	0.01	0.49^{a}	0.00
R Fore Step Length (%)	0.48^{a}	0.01	0.48^{a}	0.01	0.48^{a}	0.00	0.49^{a}	0.01
L Hind Step Length (%)	0.48^{a}	0.01	0.49^{a}	0.01	0.49^{a}	0.01	0.51^{a}	0.00
Diagonal Distance (%)	0.19^{a}	0.01	0.26^{b}	0.01	0.32^{c}	0.02	0.33^{c}	0.01
Over-stride (%)	0.31^{a}	0.02	0.23^{b}	0.01	0.17^{c}	0.01	0.16^{c}	0.01

Within a row, means without a common superscript letter differ ($P < 0.05$)

Table 2. Linear kinematic variables at all investigated ages from 3 wk to post-weaning (PW). L = Left; R = Right.

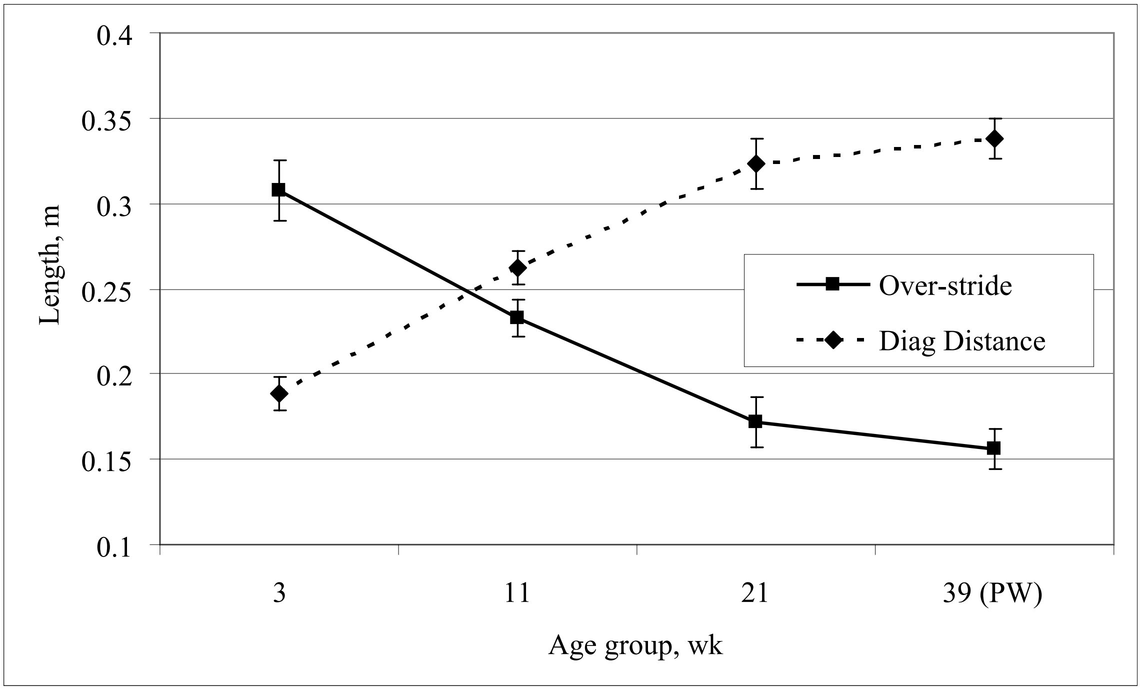


Figure 1. Mean over-stride and distance between diagonal limbs during the stance phase at 3 wk (n=9), 11 wk (n=9), 21 wk (n=9) and post-weaning (PW) (n=8) ages.

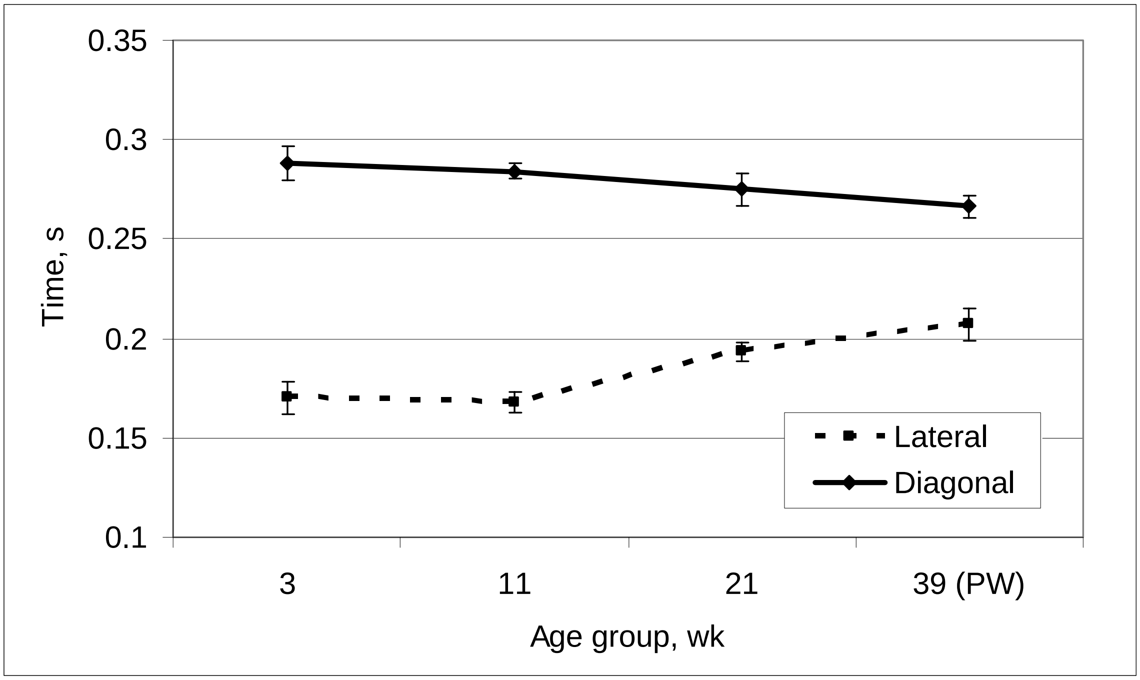


Figure 2. Mean durations between lateral pair heel strikes and diagonal pair heel strikes at 3 wk (n=9), 11 wk (n=9), 21 wk (n=9) and post-weaning (PW) (n=8) ages

CHAPTER V

Conclusions and Implications

Both conformation and linear and temporal kinematics of the walk change during early growth in warmblood foals. As expected, linear conformation measurements increase with age, with fastest growth rates within the first 7 wk for virtually all traits. After approximately 13 wk, growth slowed, though significant differences were still found for almost all traits between the post-weaning measurements and those of earlier ages. Exceptions to this trend were seen for both third metacarpal and third metatarsal bone lengths which increased minimally after birth. Most long bone lengths were correlated with wither and hip heights at all ages, supporting the idea that horses grow proportionately. With differing growth rates between connected long bones, changes in joint angle during growth were expected and realized. In agreement with previous research, scapula, humerus and tibia angles were more upright at older ages. Decreasing tibia angle correlated with the decreasing camped out stance of foals as foals aged. Hock angle also increased with age, furthering the increased straightness of the hindlimb in older foals. Possibly as a result of increasing wither height, stride length and stride duration also increased with age. Decreased over-stride and increased distance between diagonal limbs during stance at older ages possibly relate to increasing back lengths. The even 4-beat rhythm of the walk is an important judging criterion when evaluating this gait. While the difference between lateral and diagonal footfall timing decreased with age, the development of an even walk rhythm was not yet developed at the post-weaning age.

While the results of these studies are primarily in agreement with previous related research, the small number of foals investigated is cause for concern. It is possible that relevant differences were not detected due to a lack of statistical power. Further research utilizing larger sample sizes is needed to confirm the results of this study. One factor in the design of this study that limited the foals included was the number of time intervals investigated. Bi-weekly measurements were taken to ensure the detection of the timing of conformation changes. However, the time needed for marking, photographing and video taping 13 foals was typically a full 8 hours. While bi-weekly measurements are warranted during the early, fast growth, beyond approximately 13 wk of age, a less frequent measurement period may be adequate. Comparisons of kinematics recorded at a 10 wk intervals revealed significant differences for many traits. Fewer recording periods could significantly reduce the labor costs associated with this research, possibly allowing the inclusion of additional animals, increasing the power to detect differences between ages.

Additionally, to fully understand how foal conformation and gait predict adult values, studies investigating changes through adulthood are needed. Quantifying normal warmblood growth rates to adulthood are important for the development of healthy management practices for these breeds. Identifying kinematic changes through adulthood and investigating how these relate to gait quality and performance is important for the early detection of superior equine athletes. These understandings are an important step towards improved breeding, raising and maintaining of sound, athletic warmbloods.

CHAPTER VI

Literature Cited

American Hanoverian Society. 2007. Meet the 2007 inspection team. http://www.hanoverian.org/tour/bios.shtml. Accessed June 22, 2007.

American Horse Council. 2005. The economic impact of the horse industry on the United States. http://www.horsecouncil.org/statistics.htm. Accessed July 30, 2007.

Anderson, T. M., and C. W. McIlwraith. 2004. Longitudinal development of equine conformation from weanling to age 3 years in the Thoroughbred. Equine Vet. J. 36: 563-570.

Anderson, T. M., C. W. McIlwraith, and R. Douay. 2004. The role of conformation in musculoskeletal problems in the racing Thoroughbred. Equine Vet. J. 36: 571-575.

Back, W., A. Barneveld, G. Bruin, H. C. Schamhardt, and W. Hartman. 1994a. Kinematic detection of superior gait quality in young trotting warmbloods. Vet. Q. 16 (Suppl. 2): S91-96.

Back, W., A. Barneveld, H. C. Schamhardt, G. Bruin, and W. Hartman. 1994b. Longitudinal development of the kinematics of 4-, 10-, 18-and 26-month-old Dutch warmblood horses. Equine Vet. J. 17: 3–6.

Back, W., H. C. Schamhardt, and A. Barneveld. 1996. The influence of conformation on fore and hind limb kinematics of the trotting Dutch warmblood horse. Pferdeheilkunde. 12: 647-650.

Back, W., H. C. Schamhardt, W. Hartman, G. Bruin, and A. Barneveld. 1995. Predictive value of foal kinematics for the locomotor performance of adult horses. Res. Vet. Sci. 59: 64-69.

Back, W., H. C. Schamhardtt, A. Barneveld, and P. R. van Weeren. 2002. Longitudinal development of kinematics in Shetland ponies and the influence of feeding and training regimes. Equine Vet. J. 34: 609-614.

Back, W., A. J. van den Bogert, P. R. van Weeren, G. Bruin, and A. Barneveld. 1993. Quantification of the locomotion of Dutch warmblood foals. Acta Anat (Basel). 146: 141-147.

Barneveld, A. 1997. The role of breeding in sports performance and health, with special emphasis on lameness prevention. Equine Athl. 10: 36-38.

Barrey, E. 1999. Methods, applications and limitations of gait analysis in horses. Vet. J. 157: 7-22.

Barrey, E. 2001. Inter-limb coordination. Pages 77–94 in Equine Locomotion. W. Back and H. Clayton, eds. Harcourt Publishers Ltd, Philadelphia, PA.

Barrey, E., and F. Desbrosse. 1996. Lameness detection using an accelerometric device. Pferdeheilkunde. 12: 617-622.

Barrey, E., F. Desliens, D. Poirel, S. Biau, S. Lemaire, J. L. Rivero, and B. Langlois. 2002. Early evaluation of dressage ability in different breeds. Equine Vet. J. 34(Suppl.): 319-324.

Belloy, E., and A. P. Bathe. 1996. The importance of standardizing the evaluation of conformation in the horse. Equine Vet. J. 28: 429-430.

Bobbert, M. F., S. Santamaria, P. R. van Weeren, W. Back, and A. Barneveld. 2005. Can jumping capacity of adult show jumping horses be predicted on the basis of submaximal free jumps at foal age? A longitudinal study. Vet. J. 170: 212-221.

Cano, M. R., F. Miro, J.G. Monterde, A. Diz, J. Martin, and A. M. Galisteo. 2001. Changes due to age in the kinematics of trotting Andalusian foals. Equine Vet. J. 33(Suppl.): 116-121.

Clayton, H., and H. C. Schamhardt. 2001. Measurement techniques for gait analysis. Pages 55-76 in Equine Locomotion. W. Back and H. Clayton, eds. Harcourt Publishers Ltd, Philadelphia, PA.

Clayton, H. M. 1995. Comparison of the stride kinematics of the collected, medium, and extended walks in horses. Am. J. Vet. Res. 56: 849-852.

Clayton, H. M. 1999. Gait analysis comes of age. Vet. J. 157: 5-6.

Dalin, G. 1994. Pattern-recognition in equine locomotion. Equine Vet. J. 26: 173-174.

Dalin, G., and L. B. Jeffcott. 1985. Locomotion and gait analysis. Vet. Clin. North Am. Equine Pract. 1: 549-572.

Donabedian, M., G. Fleurance, G. Perona, C. Robert, S. Jacquet, J. M. Denoix, O. M. Lepage, C. Trillaud-geyl, S. Leger, and A. Ricard. 2006. Effect of fast vs. moderate growth rate related to nutrients intake on developmental orthopaedic diseases in horses. Anim. Res. 55: 471-486.

DressageDaily.com. 2006. Euro update: More than 10 million Euro for 2006 PSI auction horses. http://www.dressagedaily.com/2006/dd_200612/dd_20061220.html Accessed June 25, 2007.

Dressage World. 2007. Breeds: USA. http://www.worlddressage.com/breeds.htm Accessed Aug 17, 2007.

Faber, M., C. Johnston, P. R. van Weeren, and A. Barneveld. 2002. Repeatability of back kinematics in horses during treadmill locomotion. Equine Vet. J. 34: 235-241.

Federation Equestre Internationale. 2006. Rules for dressage events. 22nd ed. http://www.fei.org/Disciplines/Dressage/Pages/Rules.aspx Accessed Aug. 14, 2007.

Finkler-Schade, C., H. Enbergs, and L. Ahlswede. 1999. Growth development and nutrition of suckling foals. Prakt Tierarzt 80: 980-994.

Fredricson, I., S. Drevemo, G. Dalin, G. Hjerten, K. Bjorne, R. Rynde, and G. Franzen. 1983. Treadmill for equine locomotion analysis. Equine Vet. J. 15: 111-115.

Fretz, P. B., N. F. Cymbaluk, and J. W. Pharr. 1984. Quantitative-analysis of long-bone growth in the horse. Am. J. of Vet. Res. 45: 1602-1609.

Galisteo, A. M., M. R. Cano, J. L. Morales, J. Vivo, and F. Miro. 1998. The influence of speed and height at the withers on the kinematics of sound horses at the hand-led trot. Vet. Res. Comm. 22: 415-423.

Green, D. A. 1969. A study of growth rate in Thoroughbred foals. Br. Vet. J. 125: 539-546.

Green, D. A. 1976. Growth rate in thoroughbred yearlings and two year olds. Equine Vet. J. 8: 133-134.

Hannoveraner Verband. 2006. Three-day foal auction a thorough success Hanoverian top-class foal Skywalker sold at a new price record. http://www.hannoveraner.com/english/auktion/efoals2006.shtml Accessed Aug. 18, 2007

Hedge, J., and D. M. Wagoner. 2004. Horse conformation: Structure, soundness, and performance. Lyons Press, Guilford, CT.

Hickman, J., and C. Colles. 1984. Measurement of horses. Vet. Rec. 114: 491-493.

Hildebrand, M. 1965. Symmetrical gaits of horses. Science 150: 701-708.

Hintz, H. F., R. L. Hintz, and L. D. Vanvleck. 1979. Growth-rate of Thoroughbreds - effect of age of dam, year and month of birth, and sex of foal. J. Anim. Sci. 48: 480-487.

Hodson, E. F., H. M. Clayton, and J. L. Lanovaz. 1999. Temporal analysis of walk movements in the grand prix dressage test at the 1996 Olympic Games. Appl. Anim. Behav. Sci. 62: 89-97.

Holmstrom, M. 2001. Effects of conformation. Pages 281-295 in Equine Locomotion. W. Back and H. Clayton, eds. Harcourt Publishers Ltd, Philadelphia, PA.

Holmstrom, M., I. Fredricson, and S. Drevemo. 1995. Biokinematic effects of collection on the trotting gaits in the elite dressage horse. Equine Vet. J. 27: 281-287.

Holmstrom, M., L. E. Magnusson, and J. Philipsson. 1990. Variation in conformation of Swedish warmblood horses and conformational characteristics of elite sport horses. Equine Vet. J. 22: 186-193.

Holmstrom, M., and J. Philipsson. 1993. Relationships between conformation, performance and health in 4-year-old Swedish warmblood riding horses. Livest. Prod. Sci. 33: 293-312.

Hoyt, D. F., M. Molinari, S. J. Wickler, and E. A. Cogger. 2002. Effect of trotting speed, load and incline on hindlimb stance-phase kinematics. Equine Vet. J. 34: 330-336.

Hunt, W. F., V. G. Thomas, and W. Stiefel. 1999. Analysis of video-recorded images to determine linear and angular dimensions in the growing horse. Equine Vet. J. 31(Suppl.): 402-410.

Icken, W., J. Bennewitz, and E. Kalm. 2007. Analysis of auction data for horses and influence factors on pricing. Zuchtungskunde 79: 111-118.

Karaharju, E.O., S.A. Ryoppy, R.J. Makinen. 1976. Remodeling by asymmetrical epiphyseal growth. Br. J Bone Joint Surg. 58:122-126.

Kavazis, A. N., and E. A. Ott. 2003. Growth rates in Thoroughbred horses raised in Florida. J. Equine Vet. Sci. 23: 353-357.

Koenen, E. P. C., L. I. Aldridge, and J. Philipsson. 2004. An overview of breeding objectives for warmblood sport horses. Livest. Prod. Sci. 88: 77-84.

Koenen, E. P. C., A. E. Vanveldhuizen, and E. W. Brascamp. 1995. Genetic-parameters of linear scored conformation traits and their relation to dressage and show-jumping performance in the Dutch-warmblood riding horse population. Livest. Prod. Sci. 43: 85-94.

Kroekenstoel, A. M., M. C. V. van Heel, P. R. van Weeren, and W. Back. 2006. Developmental aspects of distal limb conformation in the horse: The potential consequences of uneven feet in foals. Equine Vet. J. 38: 652-656.

Leach, D., and N. F. Cymbaluk. 1986. Relationships between stride length, stride frequency, velocity, and morphometrics of foals. Am. J. Vet. Res. 47: 2090-2097.

Leach, D. H. 1987. Locomotion analysis technology for evaluation of lameness in horses. Equine Vet. J. 19: 97-99.

Leach, D. H., and W. H. Crawford. 1983. Guidelines for the future of equine locomotion research. Equine Vet. J. 15: 103-110.

Love, S., C. A. Wyse, A. J. Stirk, M. J. Stear, R. Calver, L. C. Voute, and D. J. Mellor. 2006. Prevalence, heritability and significance of musculoskeletal conformational traits in Thoroughbred yearlings. Equine Vet. J. 38: 597-603.

Lovsin, E., G. Fazarinc, A. Pogacnik, and S. V. Bavdek. 2001. Growth dynamics of Lipizzan horses and their comparison to other horse breeds. Pflugers Archiv-Eur. J. of Physiol. 442(Suppl.): R211-R212.

Magnusson, L. E. 1985a. Studies on the conformation and related traits of Standardbred trotters in Sweden. I. An objective method for measuring the equine conformation. Thesis. Swedish Univ. of Ag. Sci., Skara.

Magnusson, L. E., Thafvelin, B. 1985b. Studies on the conformation an related traits of Standardbred trotters in Sweden. II. The variation in conformation of the Standardbred trotter. Thesis. Swedish Univ. of Ag. Sci., Skara.

Magnusson, L. E., Thafvelin, B. 1985c. Studies on the conformation an related traits of Standardbred trotters in Sweden. IV. Relationships between the conformation and soundness of 4-year old Standardbred trotters. Thesis. Swedish Univ. of Ag. Sci., Skara.

Marey, E. J. 1873. La machine animale: Locomotion terestre et aerienne. Coll. Bibliotheque Science Internationale, Paris.

MathWorks, T. 1994-2007. Matlab.

Mawdsley, A., E. P. Kelly, F. H. Smith, and P. O. Brophy. 1996. Linear assessment of the Thoroughbred horse: An approach to conformation evaluation. Equine Vet. J. 28: 461-467.

Morgan, J.P., J. Neves, T. Baker. Equine radiography. Iowa State University Press, 1991. Ames, IA.

Muybridge, E. 1899. Animals in motion. Dover Publ., New York, NY.

Myers, V.S. and M.A. Emerson. 1966. The age and manner of epiphyseal closure in the forelegs of two Arabian foals. J. Amer. Vet. Radiol. Soc. 7: 39-47.

Olsson, E., A. Näsholm, E. Strandberg, and J. Philipsson. 2006. Use of field records and competition results in genetic evaluation of station performance tested Swedish warmblood stallions. Thesis. Institutionen för husdjursgenetik, Sweden.

Pagan, J. D., S. G. Jackson, and S. Caddel. 1996. A summary of growth rates of Thoroughbreds in Kentucky. Pferdeheilkunde 12: 285-289.

Parks, A. 2003. Foot balance, conformation and lameness. Pages 250-259 in Diagnosis and Management of Lameness in the Horse. S. Dyson and M. Ross eds. Saunders, St. Lewis, MO.

Peham, C., T. Licka, A. Mayr, M. Scheidl, and D. Girtler. 1998. Speed dependency of motion pattern consistency. J. Biomech. 31: 769-772.

Pool-Anderson, K., R. H. Raub, and J. A. Warren. 1994. Maternal influences on growth and development of full-sibling foals. J. Ani. Sci. 72: 1661-1666.

Preisinger, R., J. Wilkens, and E. Kalm. 1991. Estimation of genetic-parameters and breeding values for conformation traits for foals and mares in the Trakehner population and their practical implications. Livest. Prod. Sci. 29: 77-86.

Rasband, W. S. 1997-2007. ImageJ. U.S. National Institues of Health, Bethesda, MD.

Roepstorff, L., and S. Drevemo. 1993. Concept of a force-measuring horseshoe. Acta Anat (Basel) 146: 114-119.

Rooney, J.R. 1963. Diseases of the locomotor system. Pages 407-409 in Equine Medicine and Surgery. J.F. Bone, E.J. Catcott, and A.A. Gabel eds. American Vet. Publications Inc., Wheaton, IL.

Ross, M. 2003. Conformation and lameness. Pages 15-30 in Diagnosis and Management of Lameness in the Horse. M. Ross and S. Dyson eds. Saunders, St. Lewis, MO.

SAS Institute. 2002-2004. SAS 9.1.3, Cary, NC.

Schwark, H. J., P. Petzold, and I. Norenberg. 1988. Studies on the choice of selection criteria to improve riding horse breeding. Arch. Tierz. 31: 279-289.

Simi Reality Motion Systems GMBH. 2004. Simi Motion 7.0, Unterschleißheim, Germany.

Splan, R. K., S. F. Denham, and W. B. Staniar. 2007. Growth and conformation changes in warmblood horses from birth to two years of age. Proc. 20th Equine Sci. Soc., Baltimore, MD.

Staniar, W. B., D. S. Kronfeld, R. M. Hoffman, J. A. Wilson, and P. A. Harris. 2004a. Weight prediction from linear measures of growing Thoroughbreds. Equine Vet. J. 36: 149-154.

Staniar, W. B., D. S. Kronfeld, K. H. Treiber, R. K. Splan, and P. A. Harris. 2004b. Growth rate consists of baseline and systematic deviation components in Thoroughbreds. J. Anim. Sci. 82: 1007-1015.

Staniar, W. B., D. S. Kronfeld, J. A. Wilson, L. A. Lawrence, W. L. Cooper, and P. A. Harris. 2001. Growth of Thoroughbreds fed a low-protein supplement fortified with lysine and threonine. J. Anim. Sci. 79: 2143-2151.

Swedish Warmblood Association of North America. 2006. 2005 and 2006 Inspection Judges. http://www.swanaoffice.org/page_Judges2005.aspx Accessed, June 20, 2007.

Thompson, K. N. 1995. Skeletal growth-rates of weanling and yearling Thoroughbred horses. J. Anim. Sci. 73: 2513-2517.

Thompson, K. N., and B. P. Smith. 1994. Skeletal growth-patterns of Thoroughbred horses. J. Equine Vet. Sci. 14: 148-151.

Tohara, S. 1950. Radiographical studies on the ossification of legbones of horses. Jap. J. Vet. Sci. 12: 1-12.

van Weeren, P. R. 2001. History of locomotor research. Pages 1-35 in Equine Locomotion. W. Back and H. Clayton, eds. Harcourt Publishers Ltd, Philadelphia, PA.

van Weeren, P. R., and N. Crevier-Denoix. 2006. Equine conformation: Clues to performance and soundness? Equine Vet. J. 38: 591-596.

van Weeren, P. R., O. O. Sloet van, and A. Barneveld. 1999. The influence of birth weight, rate of weight gain and final achieved height and sex on the development of osteochondrotic lesions in a population of genetically predisposed warmblood foals. Equine Vet. J. 31(Suppl): 26-30.

van Weeren, P. R., A. J. van den Bogert, and A. Barneveld. 1990. Quantification of skin displacement in the proximal parts of the limbs of the walking horse. Equine Vet. J. 9(Suppl.):110-118.

van Weeren, P. R., A. J. Vandenbogert, and A. Barneveld. 1988. Quantification of skin displacement near the carpal, tarsal and fetlock joints of the walking horse. Equine Vet. J. 20: 203-208.

VanVleck, L. D., and R. Albrectsen. 1965. Differences among appraisers in the new york type appraisal program. J. Dairy Sci. 48: 61-64.

Veerkamp, R.F., C.L.M. Gerritsen, E.P.C. Koenen, A. Hamoen. 2002. Evaluation of classifiers that score linear type traits and body condition score using common sires. Journal of Dairy Science 85 (4): 976-983.

Vervuert, I., A. Borchers, M. Granel, S. Winkelsett, L. Christmann, O. Distl, E. Bruns, B. Hertsch, and M. Coenen. 2005. Estimation of growth rates in warmblood foals and the incidence of osteochondrosis. Pferdeheilkunde 21: 129-130.

Wallin, D., C. Clarke, C. Clarke, and J. Kidd. 1995. The International Warmblood Horse: A Worldwide Guide to Greeding and Bloodlines. Kenilworth Press, Addington, UK.

Weller, R., T. Pfau, D. Babbage, E. Brittin, S. A. May, and A. M. Wilson. 2006a. Reliability of conformational measurements in the horse using a three-dimensional motion analysis system. Equine Vet. J. 38: 610-615.

Weller, R., T. Pfau, S. A. May, and A. M. Wilson. 2006b. Variation in conformation in a cohort of national hunt racehorses. Equine Vet. J. 38: 616-621.

Weller, R., T. Pfau, K. Verheyen, S. A. May, and A. M. Wilson. 2006c. The effect of conformation on orthopaedic health and performance in a cohort of National Hunt racehorses: Preliminary results. Equine Vet. J. 38: 622-627.

Winter, D. A. 1990. Biomechanics and Motor Control of Human Movement. 2nd ed. John Wiley and Sons Ltd, New York, NY.

World Breeding Federation of Sport Horses. 2007. About the WBFSH. http://www.wbfsh.org Accessed Aug. 12, 2007.