ELSEVIER

Journal of Biomechanics 35 (2002) 563–571

JOURNAL
OF
BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Fetlock joint kinematics differ with age in thoroughbred racehorses

Michael T. Butcher, M.A. Ashley-Ross*

Department of Biology, Wake Forest University, P.O. Box 7325, Winston-Salem, NC-27109, USA

Accepted 23 November 2001

Abstract

Fetlock joint kinematics during galloping in 2-, 3-, 4-, and 5-year-old Thoroughbreds in race training were quantified to determine if differences due to age could account for the observation that 2-year old Thoroughbred racehorses incur a high number of injuries to the bones and soft tissues in the distal forelimbs during training and at the outset of racing. Twelve Thoroughbred racehorses were videotaped in the sagittal plane at 250 frames/s during their daily galloping workout on a 7/8 mile sand-surface training track. Four galloping strides were recorded for each horse and subsequently digitized to determine fetlock joint angles of the leading forelimb during the limb support period of a stride. Four kinematic variables were measured from each stride's angular profile: angle of fetlock joint dorsi-flexion at mid-stance, negative angular velocity, positive angular velocity and time from hoof impact to mid-stance phase of limb support. The 2-year old Thoroughbreds had significantly quicker rates of dorsi-flexion of their fetlock joints than 3- ($p = 0.01$), 4- ($p = 0.01$), and 5-year old ($p < 0.01$) Thoroughbreds following impact of the leading forelimb during moderate galloping (avg. 14 m/s). Higher rates of dorsi-flexion in young Thoroughbreds may reflect immaturity (lack of stiffness) of the suspensory apparatus tissues. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Horse; Galloping; Fetlock joint; Suspensory apparatus; Kinematics; Dorsi-flexion

1. Introduction

As a result of the evolution of the hoof, horses possess an additional effective limb joint (Hildebrand, 1960). The fetlock joint, or metacarpo-phalangeal joint in the forelimb, comprises the third metacarpal bone, two proximal sesamoid bones and the proximal phalanx bone (Getty, 1975) (Fig. 1a). The fetlock joint is unique in design in that motion is limited to the sagittal plane (Biewener, 1983; Hildebrand, 1960, 1985; Les et al., 1997), and it contains an elastic suspensory apparatus composed of the suspensory ligament, the proximal sesamoid bones and the distal sesamoidian ligaments (Bukowiecki et al., 1987). The suspensory apparatus stores and returns elastic strain energy as horses conduct locomotion (Alexander, 1984; Hildebrand, 1960, 1985). As the suspensory apparatus is being strained (lengthened) it acts as an elastic spring, storing strain energy which is instrumental in attenuating ground reaction forces generated during limb loading (Back et al., 1995a ,b; Colbourne et al., 1998; Riemersma and Schamhardt, 1985; Smith et al., 1999; Young et al., 1991), and returning strain energy via elastic recoil to economize locomotion (Alexander, 1984; Biewener, 1998; Hildebrand, 1980, 1985).

Thoroughbred racehorses are trained to race at a gallop, where the sequence of footfalls is trailing hindlimb, leading hindlimb, trailing forelimb, and leading forelimb. The period that a foot or limb is in contact with the surface is termed limb support. The leading forelimb is the last limb to leave the surface prior to suspension (period of a stride when no limbs are in contact with the surface) during galloping and as a consequence, experiences high magnitudes of limb loading (Leach and Sprigings, 1979). As horses propel themselves over the leading forelimb, their distal limb bones and soft tissues are subject to relatively greater loading than the other three limbs (Davies et al., 1993; Nunamaker et al., 1989, 1990). Thus, the limb most susceptible to overloading during galloping is the leading forelimb. Racing at near maximal galloping speeds can engender limb overloading after the distance of only one furlong (1/8 mile) has been traversed (Pratt and O' Connor, 1978) making the musculoskeletal system vulnerable to failure.

---

*Corresponding author. Tel.: +1-336-758-5965; fax: +1-336-758-6008.

E-mail address: rossma@wfu.edu (M.A. Ashley-Ross).

0021-9290/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0021-9290(01)00223-8

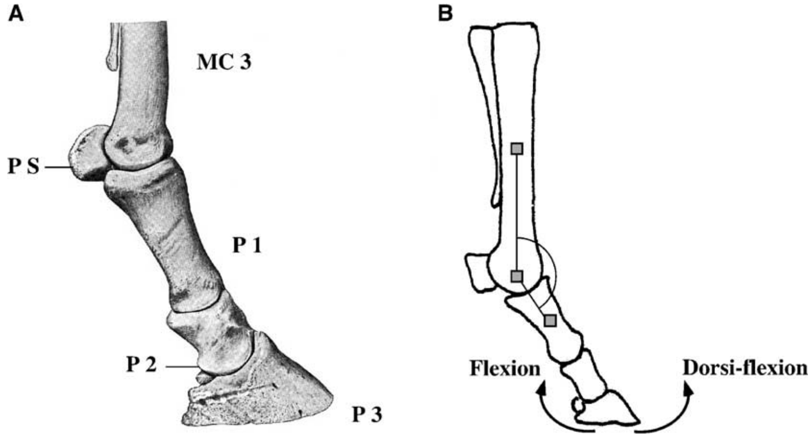

Fig. 1. Anatomy of the distal forelimb of the horse. (a) The fetlock joint is formed by the junction of the third metacarpal bone (MC3) and the proximal phalanx bone (P1). The proximal sesamoid bones (PS) (both medial and lateral) are floating bones that are situated along the palmar aspect of the fetlock joint and are contained by the suspensory ligament (not shown). (P2) and (P3) are the middle and distal phalanx bones, respectively (adapted from Getty, 1975).(b) Attachment sites of the reflective joint markers around the fetlock joint: the mid-shaft of the third metacarpal bone, the middle of the fetlock joint or the junction between the third metacarpal bone and the proximal phalanx bone, and the mid-shaft of the proximal phalanx bone. The arc defines fetlock joint angle. Arrows indicate direction of movement about the fetlock joint in the sagittal plane. Dorsi-flexion is defined as the digit being drawn towards the cranial surface of the third metacarpal bone. Flexion is defined as the digit being drawn towards the caudal surface of the third metacarpal bone (adapted from Drevemo and Johnston, 1994).

The preeminent cause of injuries in Thoroughbreds is trauma to, or failure of, the musculoskeletal system (Johnson et al., 1994). Catastrophic injuries to the superficial digital flexor tendons, proximal sesamoid bones and the third metacarpal bones of the forelimbs are common within the first two years of racing and training (Peloso et al., 1994). Two-year old Thoroughbred racehorses have a long clinical history of fatigue fractures of the third metacarpal bone during the first year of training (Nunamaker et al., 1989, 1990). A reported 70% incidence of ‘‘bucked shins’’ occurs in 2-year old Thoroughbreds in race training (Norwood, 1978; Nunamaker et al., 1989, 1990). Bucked shins (horseman jargon for bilateral fatigue fractures of the third metacarpal bones) is a condition characterized by lameness and localized soreness over the dorsal cortex of the third metacarpal bones (Nunamaker et al., 1990, 1991). Fatigue fractures are believed to result from cyclic limb loading and the subsequent mechanical fatigue damage that the developing third metacarpal bones of 2-year old Thoroughbreds experience during early intense training and ultimately racing (Nunamaker et al., 1990; Reilly et al., 1997; Stover et al., 1992). Of particular interest is that bucked shins are not commonly seen in Thoroughbred racehorses that are of age 4 years or older (Copelan, 1979; Nunamaker et al., 1989, 1990).

Whether the developing musculoskeletal system of young Thoroughbred racehorses has the ability to adapt adequately to the high magnitudes of cyclic skeletal loading experienced during training is highly debated. The purpose of this study was to quantify the influence of age on kinematics of the leading forelimb fetlock joint during limb support in Thoroughbreds during race training. Given that 2-year-old Thoroughbreds are more susceptible to lower forelimb injuries than older horses, we hypothesize that the 2-year-olds will have significantly greater amounts of dorsi-flexion and quicker rates of fetlock joint movements than older Thoroughbreds, reflecting a more compliant suspensory apparatus.

2. Materials and methods

Twelve Thoroughbred racehorses (5 males, 7 females) were selected from four different trainers at the Middleburg Thoroughbred Training Center (7/8 mile, dirt-based training track with a sand top layer) in Middleburg, Virginia. Thoroughbreds ranged in age from 2- to 5-years old. All experimental procedures conducted on these horses were within animal welfare regulations and guidelines for the United States of America.

The criterion for inclusion in this study was that each Thoroughbred had to have been in training for a minimum of three months. Specifying that all subjects were used to the rigors of training eliminated potential differences in joint kinematics as a result of musculoskeletal adaptations that occur early in race training. Thoroughbreds also had to have shown no apparent signs or symptoms of lameness just prior to and during the entire period of data collection. All age and lameness criteria were confirmed by individual trainers and corroborated by race training records.

Most Thoroughbred racehorses are trained using traditional practices (Moyer and Fisher, 1992; Nunamaker et al., 1990), involving daily galloping workouts, where the horses are warmed-up by trotting and then galloped for two laps around a training track. Following 7–10 days of daily galloping workouts, the horses are then breezed (all-out racing gallop) for 5/8 of the distance around the training track (Moyer and Fisher, 1992). After breeze workouts, the horses are given one to two days of rest. With the exception of differing days upon which horses were breezed, Thoroughbreds used in this study followed similar training regimens. On days of data collection, all horses were galloped at a similar moderate velocity gallop (open gallop) (Moyer and Fisher, 1992) near the center of the training track and ridden by similar-sized jockeys.

The right forelimb fetlock joints of the horses were marked using 3 M ScotchLite reflective tape cut in 1-in squares affixed to polo wraps commonly worn around the distal forelimbs by Thoroughbreds in race training. The polo wraps were wrapped thinly and also wrapped further down on the pastern in order to provide an attachment substrate for all markers and to circumvent potential problems with marker displacement due to polo wrap slippage. Visual inspection following the trials confirmed that all markers remained in their correct places, suggesting accurate location during experimental trials as well. The attachment sites of the reflective markers are illustrated in Fig. 1b.

Horses were videotaped at 250 frames/s using a Redlake 1000S high-speed video system with the long axis of the camera oriented perpendicular to the plane of motion of the horses (Deuel, 1994; Deuel and Lawrence, 1986; Clayton, 1993). The camera was positioned below the rail of the track and was focused to capture the motion of the lower part of the body and the limbs of the horses. The motion of the leading forelimb was videotaped as the horses were galloped past the camera on a right lead during their daily workout (Fig. 2; representative movie viewable at the Webpage of the Journal of Biomechanics: http://www.elsevier.com/locate/jbiomech). Each racehorse was videotaped four times. Captured sequences were immediately recorded to videotape using a Sony VHS VCR.

The videotaped sequences were captured to computer frame by frame using Adobe Premiere 5.0 (Adobe Systems, Inc., San Jose, CA). The custom video analysis program Didge (Alistair Cullum at the University of California, Irvine) was used to determine the (x, y) coordinates for the reflective markers around the fetlock joint for each sequence. The Didge program returns point coordinates with an interval of 0.5 units; therefore, angle values (see below) are reported as integers. Coordinates of the marker points were tracked through the entire limb support phase of the stride. Limb support can be divided into phases by three significant instants: impact, mid-stance, and breakover (Biewener, 1983, 1989; Hildebrand, 1985; Fig. 2). Impact is the instant when the hoof stops sliding forward after it makes the initial contact with the surface (Fig. 2a). Mid-stance is the instant when the fetlock joint is maximally dorsi-flexed (Fig. 2c). Finally, breakover is the instant when only the toe of the hoof is in contact with the surface, immediately prior to limb suspension (Clayton, 1993) (Fig. 2e).

The coordinate files were imported into Microsoft Excel (Microsoft Corp., Redmond, WA), which was used to compute the angle of the fetlock joint for each frame of the sequences (Fig. 1b). Reliability of kinematic measurements was checked by digitizing the same angle 100 times; the 95% confidence interval was found to be 0.4 degrees. Angular data were then smoothed to reduce digitizing error by Gaussian filtering using the curve-fitting and analysis program Igor Pro (WaveMetrics, Inc.,

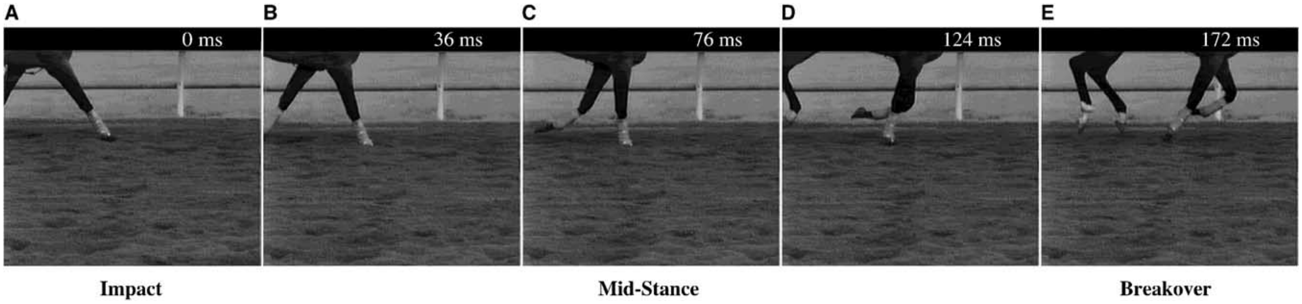

Fig. 2. Fetlock joint motion during limb support. Panels are high-speed video images (250 frames/s) of a forelimb motion sequence of one individual Thoroughbred racehorse. (a) Leading forelimb (right forelimb) hoof impacts the surface beginning limb support. (b) Fetlock joint is undergoing dorsi-flexion as the leading forelimb is being loaded by the weight of the horse. (c) Fetlock joint achieves its most acute angle of dorsi-flexion at mid-stance. (d) Fetlock joint is undergoing flexion as the horse's body passes over the leading forelimb and the limb is being unloaded. (e) Leading forelimb hoof is preparing to leave the surface at breakover as the forelimb is being retracted.

Lake Oswego, OR). The smoothed angular profiles were used to determine four kinematic variables: angle of dorsi-flexion at mid-stance, negative angular velocity, positive angular velocity, and time from impact to mid-stance.

Negative and positive angular velocities were determined by differentiation of the joint angle vs. time curves. Negative angular velocity was defined as the rate of angular change from impact to mid-stance (rate of dorsi-flexion) while positive angular velocity was defined as the rate of angular change from mid-stance to breakover (rate of flexion). Velocity of galloping was determined by tracking the movement of the horse's body through a known distance, and dividing the distance traveled by the time taken for the sequence.

A mixed design repeated measures MANOVA for random measurements (SAS; SAS Institute Inc., Cary, NC) was employed to test for differences in the kinematics of the leading forelimb fetlock joint among the age classes of Thoroughbreds (2-, 3-, 4-, and 5-year olds). The criterion for significance for all repeated measures F-values was $p \leqslant 0.05$. Tukey's post hoc tests were used to follow-up significant F-values. To insure that effects of velocity would not confound the interpretation of the MANOVA age results, a series of linear regression analyses (StatView; SAS Institute Inc., Cary, NC) were performed on all data to determine the strength of the relationships between the kinematic variables and velocity of galloping. All data met the assumptions of normality, homoscedasticity and outliers, validating both repeated measures MANOVA and regression results.

3. Results

The rate of fetlock joint dorsi-flexion from impact to mid-stance (negative angular velocity) differed significantly among the four single-year age classes of Thoroughbred racehorses (repeated measures MANOVA; $F = 3.67, p = 0.02$). The 2-year old Thoroughbreds were found to exhibit the greatest mean negative angular velocity (Table 1). Post hoc tests revealed that the 2-year old age class displayed a significantly quicker rate of fetlock joint dorsi-flexion than the 3- ($p = 0.01$), 4- ($p = 0.01$), and 5-year old ($p < 0.01$) age classes (Table 1). In general, as age increased from 2- to 5-years old, the rate of fetlock joint dorsi-flexion from impact to mid-stance appeared to decrease (Fig. 4). The only exception to this general trend was the slight deviation in the rate of dorsi-flexion found for the 3-year old age class, which was equivalent to that of the 4-year old age class (Table 1). Regression analysis found no significant correlation between negative angular velocity and the velocity of galloping (Table 2), among all data or within the individual age classes (Fig. 3). In fact, the velocity of galloping accounted for almost zero variance in negative angular velocity within the range of moderate galloping speeds analyzed (Table 2).

The angle of dorsi-flexion at mid-stance was not significantly different ($p = 0.24$) among the four single-year age classes of Thoroughbreds (Fig. 5). The 5-year old age class displayed the most acute angle of dorsi-flexion at mid-stance, but reached this value more slowly than the other age classes (Table 1). The angle of dorsi-flexion did appear to decrease with increased velocity of

Table 1
Mean ± SD of both leading forelimb fetlock joint kinematic variables and galloping velocity for single-year age classes of Thoroughbred racehorses

	Angle of dorsi-flexion at mid-stance (deg)	Negative angular velocity (-deg/ms)	Positive angular velocity (deg/ms)	Time from impact to mid-stance (ms)	Velocity of galloping (m/s)
2-year old ($n = 3$)	102 ± 6.0	(-) 1.6 ± 0.30*	1.8 ± 0.33	43.7 ± 17.43	14.7 ± 3.10
3-year old ($n = 3$)	106 ± 7.1	(-)1.3 ± 0.39	1.5 ± 0.24	46.3 ± 18.09	12.6 ± 1.62
4-year old ($n = 4$)	102 ± 8.3	(-)1.3 ± 0.21	1.8 ± 0.49	50.5 ± 14.30	14.0 ± 3.03
5-year old ($n = 2$)	97 ± 3.4	(-)1.2 ± 0.30	1.9 ± 0.36	46.5 ± 10.46	16.1 ± 4.06

*Significance at $p \leqslant 0.05$ as determined by Tukeys' post hoc test.

Table 2
Summary of linear regressions of the effect of galloping velocity on leading forelimb fetlock joint kinematic variables

Kinematic variable	Correlation coefficient (R)	R squared	F-value	P-value
Angle of dorsi-flexion at mid-stance	0.227	0.052	2.507	0.1202
Negative angular velocity	0.047	0.002	0.101	0.7525
Positive angular velocity	0.186	0.035	1.644	0.2062
Time from impact to mid-stance	0.103	0.011	0.495	0.485

No kinematic variable was found to be significantly correlated with the speed of galloping.

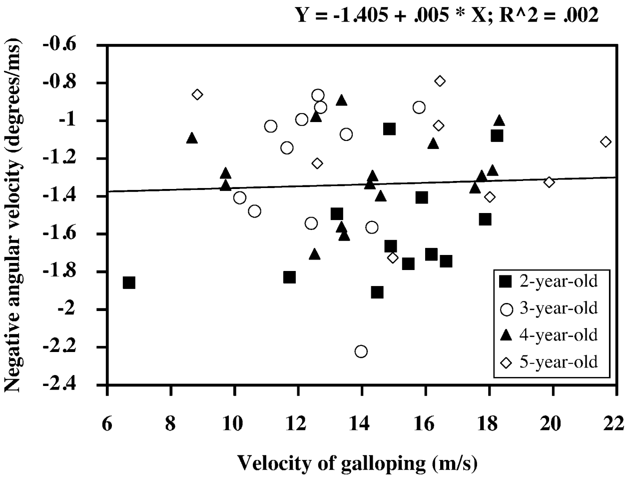

Fig. 3. Regression plot for negative angular velocity and velocity of galloping. Negative angular velocity was the variable found to have the weakest correlation of any kinematic variable with galloping velocity. The near flat regression line depicts the lack of a significant correlation ($R = 0.047$; $p = 0.75$) between the two variables. Velocity accounted for an extremely small proportion of the variance in the negative angular velocity (R^2=0.002). Age classes are denoted by the different symbols.

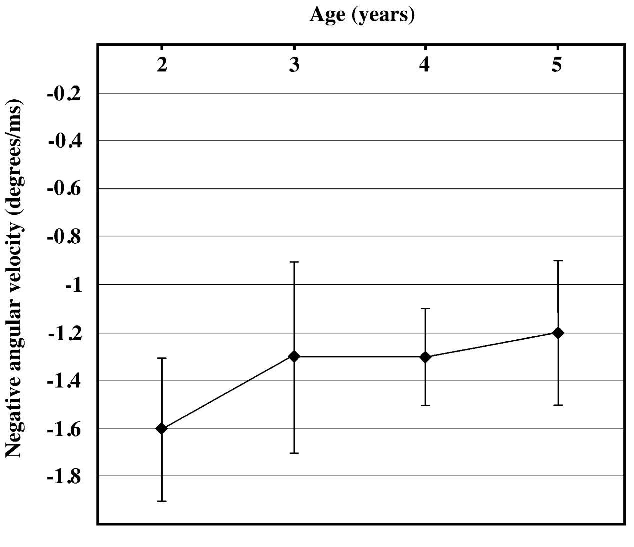

Fig. 4. General trend of negative angular velocity (rate of fetlock joint dorsi-flexion from impact to mid-stance) for single-year age classes of Thoroughbred racehorses. More negative numbers indicate higher rates of dorsi-flexion. Error bars are SD. Negative angular velocity appeared to decrease with age from 2- to 5-years old, and was found to differ significantly ($p = 0.02$) among the four single-year age classes of Thoroughbreds. Tukey's post hoc test for repeated measures MANOVA revealed significant differences between 2-year old Thoroughbreds and each of the remaining single-year age classes.

galloping (Fig. 6); however, the correlation was not significant (Table 2). The positive angular velocity and time from impact to mid-stance did not differ significantly among the four single-year age classes (Table 1).

The time from impact to mid-stance generally appeared to increase with age from 2- to 5-years old (Fig. 5). The average time from impact to mid-stance was the least for the 2-year old age class which is in accord with the finding of a significantly higher negative angular velocity for the 2-year old racehorses relative to the 3-, 4-, and 5-year old Thoroughbreds. The time from impact to mid-stance was not significantly correlated with the velocity of galloping (Table 2).

4. Discussion

The objective of this study was to test the hypothesis that 2-year old Thoroughbreds would demonstrate significantly greater amounts of dorsi-flexion and quicker rates of fetlock joint movements than older Thoroughbreds, correlating with the higher incidence of forelimb injuries in young racehorses. Statistical analysis of fetlock joint kinematics revealed that 2-year old Thoroughbreds have significantly quicker rates of fetlock joint dorsi-flexion than older Thoroughbreds following impact of the leading forelimb during moderate galloping. Taking into account the small sample size, this finding was considered to be suggestive of ontogenetic differences in the rate of dorsi-flexion between 2-year olds and older Thoroughbred racehorses. Additionally, the lack of a significant relationship between velocity of galloping and negative angular velocity further argues for real age-related differences in the rate of fetlock joint dorsi-flexion.

The quicker rate of fetlock joint dorsi-flexion in the 2-year old Thoroughbreds compared to the older age classes may be related to the stiffness of the suspensory apparatus, which is thought to reflect the maturity/immaturity of the tissues (Smith et al., 1999). Presumably, older Thoroughbreds have a suspensory apparatus that is stiffer relative to the same tissues of younger Thoroughbreds. Bukowiecki et al. (1987) have demonstrated that the suspensory apparatus of trained racehorses in vitro was stronger than in untrained racehorses. Thoroughbred racehorses are generally considered to be musculoskeletally mature around age 4 (Copelan, 1979); however; individual horses may require longer periods for the musculoskeletal system to fully mature due to the superimposition of intense training on growth and development (Nunamaker et al., 1990; Young et al., 1991). Therefore, it is reasonable to suggest that the suspensory apparatus tissues of young Thoroughbreds may be immature and have not completely adapted to cyclic strain experienced during race training. Thus, the suspensory apparatus of 2-year old Thoroughbred racehorses would be less resistant to deformation and allow for the

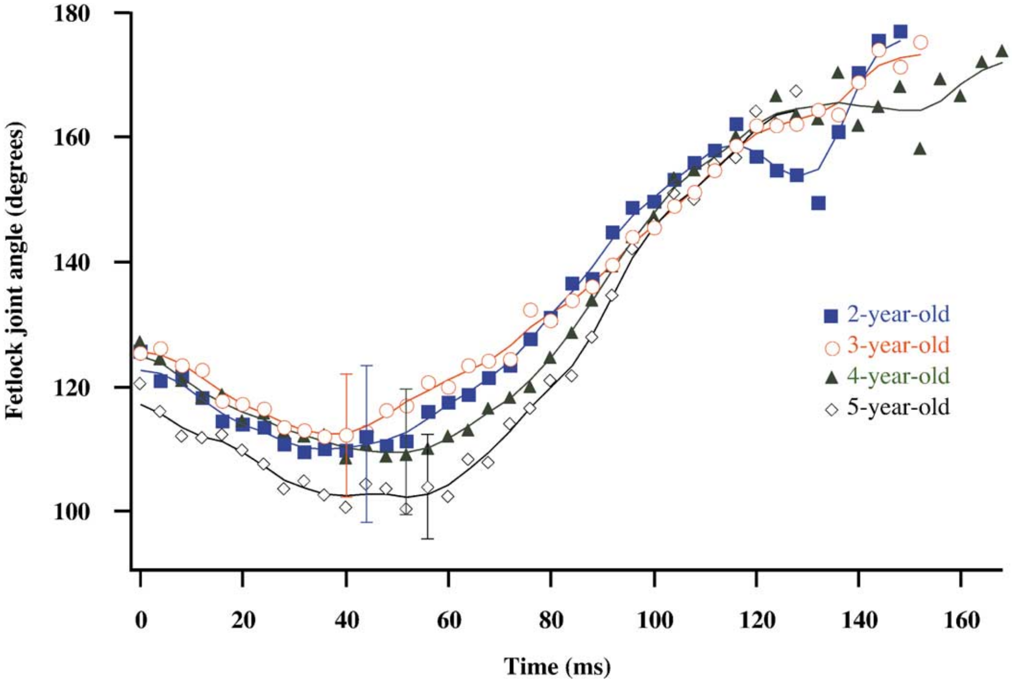

Fig. 5. Comparison of mean fetlock joint angle vs. time curves for single-year age classes of Thoroughbred racehorses during limb support. Time 0 (ms) is the time of leading forelimb impact, while the lowest point on each curve represents the time of leading forelimb mid-stance. Error bars show the average standard deviation for each curve. The angle of fetlock joint dorsi-flexion at mid-stance did not differ significantly among the four single-year age classes of Thoroughbreds. The time from forelimb impact to mid-stance appeared to increase with age from 2- to 5-years old.

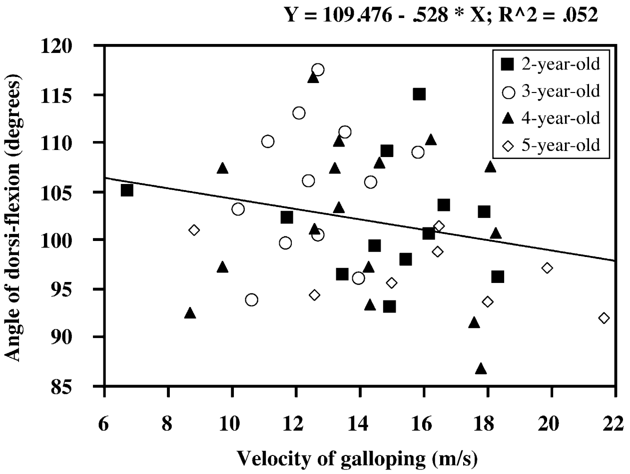

Fig. 6. Regression plot for angle of dorsi-flexion at mid-stance and velocity of galloping. Angle of dorsi-flexion at mid-stance was not significantly correlated ($R = 0.227$; $p = 0.12$) with the velocity of galloping. However, the angle of dorsi-flexion at mid-stance had the strongest correlation of any kinematic variable with galloping velocity. The negative slope of the regression line demonstrates that the angle of dorsi-flexion decreases (greater amount of dorsi-flexion) as velocity increases. Age classes are denoted by the different symbols.

significantly greater rate of fetlock joint dorsi-flexion following impact of the leading forelimb during galloping (Fig. 4; Table 1).

Suspensory apparatus tissue that is less stiff may store less elastic strain energy upon limb loading. The data showed a trend of increasing time from impact to mid-stance as horses increase in age from 2- to 5-years old (Fig. 5; Table 1). An increase in time over which force is applied allows for greater ground reaction force attenuation. Therefore, 2-year old Thoroughbreds may have reduced shock absorption relative to the older Thoroughbreds. Although this hypothesis requires further investigation, reduced shock absorption would increase the magnitude and possibly the rate of limb loading in 2-year old Thoroughbreds. High loading rates can alter the material and mechanical properties of bone, making them brittle and less stiff (Davies et al., 1993), and render immature bones susceptible to bone fatigue (Evans et al., 1992; Reilly et al., 1997). This could help to explain the high incidence of third metacarpal bone fatigue fractures experienced by 2-year old Thoroughbreds in race training.

Suspensory apparatus stiffness could also be associated with fetlock joint range of motion. On average, 2-year old Thoroughbreds displayed greater dorsi-flexion at mid-stance than 3-year olds (Table 1). The less acute dorsi-flexion for the 3-year old age class may represent the adaptation of increased suspensory apparatus stiffness as a result of one additional year of training. Gillis et al. (1993) have shown that the digital flexor

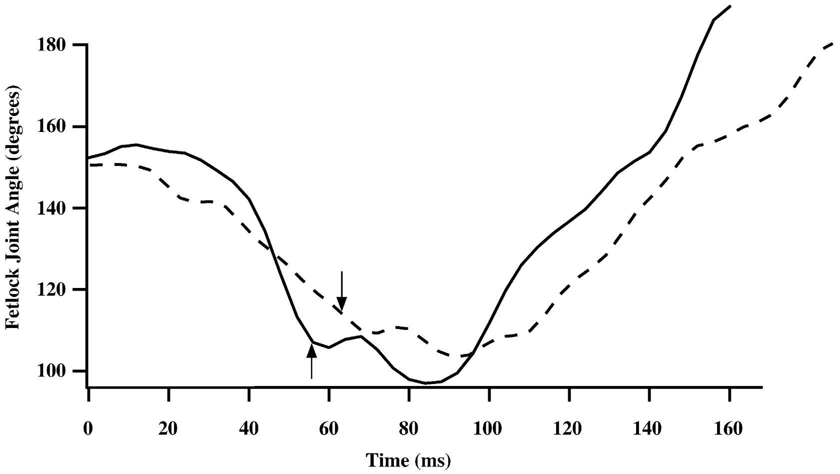

Fig. 7. Fetlock joint angle vs. time curve for one individual Thoroughbred during limb support while breezing (racing gallop workout). A fetlock joint angle profile of the same individual racehorse galloping (dashed curve) at an open gallop has been superimposed on the breezing angular profile. The arrows indicate the time of hoof impact. On the breezing fetlock angle vs. time curve (solid curve) note the more rapid decrease in fetlock joint angle preceding impact as the hoof is sliding, and the more acute angle of dorsi-flexion.

tendons undergo an increase in mean cross-sectional area during the first four months of race training. A similar increase in cross-sectional area of the suspensory ligament is likely. Thus, 2-year old Thoroughbreds may show more acute angles of dorsi-flexion because of an immature suspensory apparatus. Conversely, 4- and 5-year olds show greater amounts, but slower rates of dorsi-flexion. This suggests greater shock absorption by a mature suspensory apparatus, allowing freedom of movement which is indicative of soundness and joint suppleness (Back et al., 1994). Increased force attenuation may be particularly important at racing velocities. Over the course of data collection, some breezing sequences of a few individual Thoroughbreds used in the study were videotaped. During breezing, both the amount of dorsi-flexion at mid-stance and negative angular velocity appear to significantly increase (Fig. 7). Since limb loading is known to increase with increasing speed (Biewener et al., 1983b; Davies et al., 1993), dangerously high magnitudes of strain developed in the bones and soft tissues comprising the fetlock joint may alter leading forelimb fetlock joint kinematics during breezing and cause unaccustomed third metacarpal bone bending (Bertram and Biewener, 1988; Biewener et al., 1983a, b). Thus, the chances of fracture are increased while breezing due to greater bending loads acting on the leading forelimbs with each footfall.

In conclusion, forelimb injuries have been shown to decrease with age, maturation, adaptive bone remodeling, and adaptation through exercise which all serve to increase the stiffness and toughness of skeletal tissues (Nunamaker et al., 1989, 1990; Reilly et al., 1997; Reilly and Currey, 1999; Smith et al., 1999; Stover et al., 1992; Young et al., 1991). Furthermore, it is known that young age is a major factor involved in fatigue fractures of the forelimb third metacarpal bones (Nunamaker et al., 1990). While it has been suggested that kinematics do not change significantly with age/ontogeny (Back et al., 1995a ,b), the rate of fetlock joint dorsi-flexion was shown to be significantly related to age and offers a potentially fruitful area of future study. Our findings suggest that 2-year old Thoroughbreds may be too immature to train safely according to traditional regimens. Further studies of tissue material properties, and how they change according to age and training across a range of gaits and speeds, must be done to answer finally the question of why young Thoroughbreds are particularly susceptible to distal forelimb injury.

Acknowledgements

We thank F. Fregin and N. White of the Marion DuPont Scott Equine Medical Center in Leesburg, Virginia for direction in the early stages of the study. R. Gargagliano for being generous with time and equipment. B. Cohencious for imaging knowledge and videotaping equipment. We thank P. Fout for permitting us to videotape horses at the Middleburg training center. J. Rolfe, J. Johnson, D. Yovanovich and C. Colbe for providing the racehorses that were used in the study and for working so patiently with us over the course of two months. A very special thanks is addressed to A. Phillipe for her steadfast dedication and skillful camera work. We thank R. Browne and W. Lang for helpful assistance with data analysis. S. Messier for critical comments and advice. This work was supported in part by a grant from the National Science Foundation (IBN-9813730) to MA-R

References

Alexander, R.McN., 1984. Elastic energy stores in running vertebrates. American Zoologist 24, 85–94.

Back, W., Barneveld, A., Bruin, G., Schamhardt, H.C., Hartman, W., 1994. Kinematic detection of superior gait quality in young warmbloods. Veterinary Quarterly 16 (Suppl. 2), 91–96.

Back, W., Schamhardt, H.C., Hartman, W., Bruin, G., Barneveld, A., 1995a. Predictive value of foal kinematics for the locomotor performance of adult horses. Research in Veterinary Science 59, 64–69.

Back, W., Schamhardt, H.C., Savelberg, H.H., van den Bogert, A.J., Bruin, G., Hartman, W., Barneveld, A., 1995b. How the horse moves: 1. Significance of graphical representations of equine forelimb kinematics. Equine Veterinary Journal 27, 31–38.

Bertram, J., Biewener, A.A., 1988. Bone curvature: sacrificing strength for load predictability? Journal of Theoretical Biology 131, 75–92.

Biewener, A.A., 1983. Allometry of quadrupedal locomotion: the scaling of duty factor, bone curvature and limb orientation to body size. Journal of Experimental Biology 105, 147–171.

Biewener, A.A., 1989. Scaling body support in mammals: limb posture and muscle mechanics. Science 245, 45–48.

Biewener, A.A., 1998. Muscle–tendon stresses and elastic energy storage during locomotion in the horse. Comparative Biochemistry and Physiology Part B 120, 73–87.

Biewener, A.A., Thomason, J., Goodship, A., Lanyon, L.E., 1983a. Bone stress in the horse forelimb during locomotion at different gaits: a comparison of two experimental methods. Journal of Biomechanics 16, 565–576.

Biewener, A.A., Thomason, J., Lanyon, L.E., 1983b. Mechanics of locomotion and jumping in the forelimb of the horse (*Equus*): in vivo stress developed in the radius and metacarpus. Journal of Zoology. London 201, 67–82.

Bukowiecki, C.F., Bramlage, L.R., Gabel, A.A., 1987. In vitro strength of the suspensory apparatus in training and in resting horses. Veterinary Surgery 16, 126–130.

Clayton, H.M., 1993. The extended canter: a comparison of some kinematic variables in horses trained for dressage and for racing. Acta Anatomica 146, 183–187.

Colbourne, G.R., Lanovaz, J.L., Sprigings, E.J., Schamhardt, H.C., Clayton, H.M., 1998. Forelimb joint moments and power during the walking stance phase of horses. American Journal of Veterinary Research 59, 609–614.

Copelan, R.W., 1979. Incidence, location, and principles of treatment of the stress fractures of the third metacarpal bone. Proceedings of the American Association of Equine Practitioners 25, 159–162.

Davies, H.M.S., McCarthy, R.N., Jeffcott, L.B., 1993. Surface strain on the dorsal metacarpus of Thoroughbreds at different speeds and gaits. Acta Anatomica 146, 148–153.

Deuel, N.R., 1994. Coordination of equine forelimb motion during the gallop. Equine Veterinary Journal Supplemental 17, 29–34.

Deuel, N.R., Lawrence, L.M., 1986. Gallop velocity and limb contact variables of quarter horses. Journal of Equine Veterinary Science 6, 143–147.

Drevemo, S., Johnston, C., 1994. The use of a panning technique in equine kinematic analysis. Equine Veterinary Journal (Supplement) 17, 39–43.

Evans, G.P., Behiri, J.C., Vaughan, L.C., Bonfield, W., 1992. The response of equine cortical bone to loading strain rates experienced in vivo by the galloping horse. Equine Veterinary Journal. 24, 125–128.

Getty, R., 1975. Osteology. In: Rosenbaum, C.E., Ghoshal, N.G., Hillman, D. (Eds.), Sisson and Grossman: The Anatomy of the Domestic Animals. W. B. Saunders Company, London, pp. 255–348.

Gillis, C.L., Meagher, D.M., Pool, R.R., Stover, S.M., Craychee, T.J., Willits, N., 1993. Ultrasonographically detected changes in equine superficial digital flexor tendons during the first months of race training. American Journal of Veterinary Research 54, 1797–1802.

Hildebrand, M., 1960. How animals run. Scientific American 202, 148–157.

Hildebrand, M., 1980. The adaptive significance of tetrapod gait selection. American Zoologist 20, 255–267.

Hildebrand, M., 1985. Walking and running. In: Hildebrand, M., Bramble, D.M., Liem, K.F., Wake, D.B. (Eds.), Functional Vertebrate Morphology. Belknap press of Harvard University press, Cambridge, MA, pp. 38–57.

Johnson, B.J., Stover, S.M., Daft, B.M., Kinde, H., Read, D.H., Barr, B.C., Anderson, M., Moore, J., Woods, L., Stotlz, J., Blanchard, P., 1994. Causes of death in racehorses over a 2 year period. Equine Veterinary Journal 26, 327–330.

Leach, D.H., Sprigings, E., 1979. Gait fatigue in the racing Thoroughbred. Journal of Equine Medicine and Surgery 3, 436–443.

Les, C.M., Stover, S.M., Keyak, J.H., Taylor, K.T., Willits, N.H., 1997. The distribution of material properties in the equine third metacarpal bone serves to enhance sagittal bending. Journal of Biomechanics 30, 355–361.

Moyer, W., Fisher, J.R.S., 1992. Bucked shins: effects of differing track surfaces and proposed training regimens. Proceedings of the American Association of Equine Practitioners 37, 541–547.

Norwood, G.L., 1978. The bucked-shin complex in Thoroughbreds. Proceedings of the American Association of Equine Practitioners 24, 319–336.

Nunamaker, D.M., Butterweck, D.M., Provost, M.T., 1989. Some geometric properties of the third metacarpal bone: a comparison between the Thoroughbred and Standardbred racehorse. Journal of Biomechanics 22, 129–133.

Nunamaker, D.M., Butterweck, D.M., Provost, M.T., 1990. Fatigue fractures in Thoroughbred racehorses: relationships with age, peak bone strain, and training. Journal of Orthopedic Research 8, 604–611.

Nunamaker, D.M., Butterweck, D.M., Black, J., 1991. In vitro comparison of Thoroughbred and standardbred racehorses with regard to local fatigue failure of the third metacarpal bone. American Journal of Research 52, 97–100.

Peloso, J.G., Mundy, G.D., Cohen, N.D., 1994. Prevalence of, and factors associated with, musculoskeletal racing injuries of Thoroughbreds. Journal of the American Veterinary Medical Association 204, 620–626.

Pratt, G.W., O'Connor, J.T., 1978. A relationship between gait and breakdown in the horse. American Journal of Veterinary Research 39, 249–253.

Reilly, G.C., Currey, J.D., 1999. The development of microcracking and failure in bone depends on the loading mode to which it has adapted. Journal of Experimental Biology 202, 543–552.

Reilly, G.C., Currey, J.D., Goodship, A.E., 1997. Exercise of young Thoroughbred horses increases impact strength of the third metacarpal bone. Journal of Orthopedic Research 15, 862–868.

Riemersma, D.J., Schamhardt, H.C., 1985. In vitro mechanical properties of equine tendons in relation to cross-sectional area and collagen content. Research in Veterinary Science 39, 263–270.

Smith, R.K., Birch, H., Patterson-Kane, J., Firth, E.C., Williams, L., Cherdchutham, W., van Weeran, W.R., Goodship, A.E., 1999.

Should equine athletes commence training during skeletal development?: changes in tendon matrix associated with development, ageing, function and exercise. Equine Veterinary Journal Supplemental 30, 201–209.

Stover, S.M., Pool, R.R., Martin, R.B., Morgan, J.P., 1992. Histological features of the dorsal cortex of the third metacarpal bone mid-diaphysis during postnatal growth in thoroughbred horses. Journal of Anatomy 181, 455–469.

Young, D.R., Nunamaker, D.M., Markel, M.D., 1991. Quantitative evaluation of the remodeling response of the proximal sesamoid bones to training-related stimuli in Thoroughbreds. American Journal of Veterinary Research 52, 1350–1355.