Moment arms about the carpal and metacarpophalangeal joints for flexor and extensor muscles in equine forelimbs

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Objective—To determine whether muscle moment arms at the carpal and metacarpophalangeal joints can be modeled as fixed-radius pulleys for the range of motion associated with the stance phase of the gait in equine forelimbs.

Sample Population—4 cadaveric forelimbs from 2 healthy Thoroughbreds.

Procedure—Thin wire cables were sutured at the musculotendinous junction of 9 forelimb muscles. The cables passed through eyelets at each muscle's origin, wrapped around single-turn potentiometers, and were loaded. Tendon excursions, measured as the changes in lengths of the cables, were recorded during manual rotation of the carpal (180° to 70°) and metacarpophalangeal (220° to 110°) joints. Extension of the metacarpophalangeal joint (180° and 220°) was forced with an independent loading frame. Joint angle was monitored with a calibrated potentiometer. Moment arms were calculated from the slopes of the muscle length versus joint angle curves.

Results—At the metacarpophalangeal joint, digital flexor muscle moment arms changed in magnitude by ≤ 38% during metacarpophalangeal joint extension. Extensor muscle moment arms at the carpal and metacarpophalangeal joints also varied (≤ 41% at the carpus) over the range of joint motion associated with the stance phase of the gait.

Conclusions and Clinical Relevance—Our findings suggest that, apart from the carpal flexor muscles, muscle moment arms in equine forelimbs cannot be modeled as fixed-radius pulleys. Assuming that muscle moment arms at the carpal and metacarpophalangeal joints have constant magnitudes may lead to erroneous estimates of muscle forces in equine forelimbs. (*Am J Vet Res* 2003;64:351–357)

Articular and musculotendinous injuries in the forelimbs of athletic horses are associated with extremely large repetitive loads during the stance phase of the gait. Although external forces resulting from ground contact have been measured,[1-5] quantification of muscle and joint contact forces requires a detailed model of forelimb musculoskeletal geometry. By use of such a model, muscle forces that are dependent on muscle moment arms can be determined and used to estimate the forces transmitted by the joints during phases of the gait. A more detailed knowledge of muscle and joint contact forces will increase understanding of injuries to athletic horses and may lead to improvements in treatment and prevention.

The tendency of a muscle to rotate a bone about a joint is described by the moment arm of that muscle. Muscle moment arms typically vary with joint angle; thus, knowledge of the changes in magnitudes of these quantities with joint position is important for understanding muscle function during many activities, including locomotion. Knowledge of muscle moment arms is also useful in the validation of musculoskeletal models that are used to predict muscle forces. Comparisons between experimentally measured moment arms and those calculated in a model can be used to validate the muscle paths assumed in the model.

Muscle moment arms are estimated by means of geometric or tendon-excursion methods.[6-12] In the distal portion of forelimbs of horses, moment arms have been estimated by use of geometric methods[7,13,14]; in those studies, fixed centers of rotation for the carpal and metacarpophalangeal joints were assumed, and moment arms were determined via measurement of distances from the joint centers to the lines of action of the muscles that act about these joints. If moment arms of constant magnitudes are assumed, computation of muscle forces during equine locomotion is made easier, because constant moment arms simplify the geometry of the musculoskeletal system.[7,13,14,a] However, it is not known whether lines of action of muscles acting on the carpal and metacarpophalangeal joints remain at fixed distances from the respective centers of rotation.

If moment arms of the muscles at the carpal and metacarpophalangeal joints can be modeled as constants independent of changes in joint angles, then simple musculoskeletal models of equine forelimbs will be sufficient to study muscle function. However, if moment arms vary substantially with joint angle, previous estimates of muscle forces in equine forelimbs become questionable. The purpose of the study reported here was to determine whether the moment arms of muscles crossing the carpal and metacarpophalangeal

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joints of equine forelimbs remain constant across the range of joint angles observed during the stance phase of the gait.[1,3,5] Moment arms for 9 muscles in equine forelimbs were measured by the tendon-excursion method to test the hypothesis that fixed-radius pulleys can be used to represent moment arms for muscles crossing the carpal and metacarpophalangeal joints.

Materials and Methods

Tendon excursions and joint angles were measured in forelimbs obtained from 2 Thoroughbred horses.[b] Horses were sedated with xylazine and euthanatized with a barbiturate overdose or magnesium sulfate and potassium chloride administered IV. On gross examination, limbs appeared free from musculoskeletal disease.

Limbs were stored at –20°C and individually thawed at room temperature (25°C) prior to data collection. Ice packs were applied to the limbs between testing periods. Skin was removed from each limb on the day of testing. The scapula and brachialis, biceps brachii, triceps brachii, and anconeus muscles were removed. All other muscles, ligaments, and joint capsule structures of the distal portion of the limb remained in situ. The suspensory ligament remained intact throughout the study.

Nylon-coated, stranded, stainless-steel fishing leader wires were sutured at the superficial aspect of the musculotendinous junction of 9 muscles. Wires were routed through 1-mm-diameter polyethylene sheaths to protect the muscles and provide low-friction channels for the wire cables. Eleven muscle bellies from 9 muscles were instrumented for measurement of tendon excursions about the carpal joint, whereas 6 bellies from 4 muscles remained instrumented for measurement of tendon excursions about the metacarpophalangeal joint **(Fig 1)**. Two wires were sutured at the same location at the musculotendinous junction of the deep digital flexor and common digital extensor, because these muscles have multiple heads. The ulnar head of the flexor carpi ulnaris muscle was not instrumented. Only data for the larger humeral heads of the deep digital flexor muscle and the common digital extensor muscle were reported here, because moment arms for the ulnar heads were similar to those of their respective humeral heads.

Muscle origins were maintained by routing the wires through eyelets that were screwed into respective origins. The polyethylene sheath was tacked to the muscle belly, and a running suture was made along each muscle belly to maintain the path of the sheath. To approximate the centroid path of the extensor carpi radialis muscle, the polyethylene sheath was placed within a longitudinal incision made in the muscle and secured with a running suture. The tendon of the extensor carpi radialis muscle was cut to allow full flexion of the carpal joint. No other tendons were released via cutting.

Passing through their respective origins, the wire cables were routed through the testing frame and wrapped around single-turn precision potentiometers (0.5% linearity) for measurement of tendon excursion.[11] After connection to the potentiometer, a 1.83-kg weight (to generate a force of 18 N) was attached to each cable to remove slack in the tendon and overcome friction during joint motion **(Fig 2)**. After attachment of the weight, the preparation was allowed to stabilize for ≥ 15 minutes to reduce the effect of tendon creep[12,15]; rotations of the joints were performed slowly to reduce errors associated with viscoelastic properties of tendon.[6]

Measurement equipment was calibrated prior to testing each limb by use of a precision-machined acrylic plastic hinge model, in accordance with the method of Buford et al.[11] The acrylic plastic hinge has 2 fixed-radius moment arms (5.08 and 4.45 cm) and a protractor etched at 1° intervals about the hinge's axis. Resultant accuracy calculations from the calibration were ± 2° for joint angle and ± 0.1 mm for change in muscle length. The measured muscle moment arm for the acrylic plastic model was repeatable and accurate to ± 0.4 mm.

Joint angles were defined at the caudal aspect of each joint, whereby an extended position of the limb yielded joint angles of 180° **(Fig 3)**. Flexion of the carpal and metacarpophalangeal joints decreased these joint angles. The elbow and proximal and distal interphalangeal joints were fixed with 5-mm transarticular Steinman pins at 210°, 180°, and 180°, respectively. In all limbs, tendon excursions about the carpal joint were performed first while the metacarpophalangeal joint was fixed via a transarticular Steinman pin. After testing of the carpal joint, the Steinman pin, placed along the long

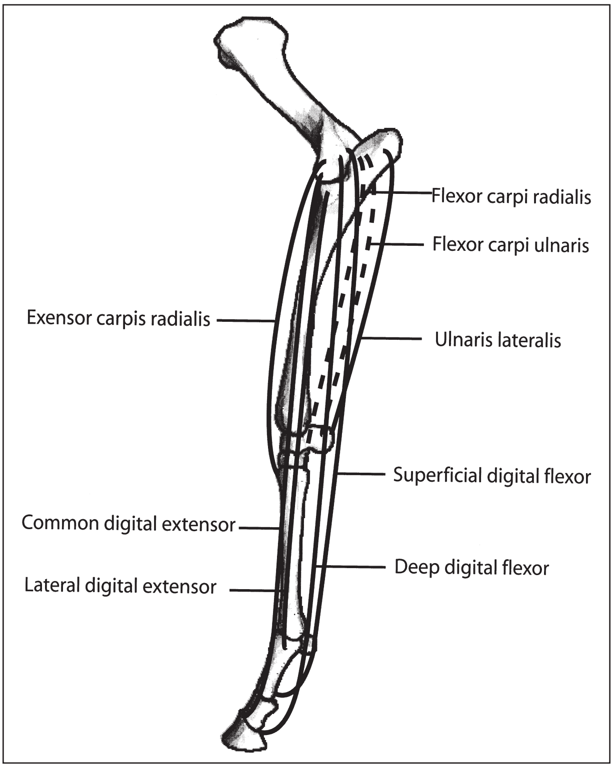

Figure 1—Illustration of the lateral aspect of the forelimb of a horse indicating muscles for which moment arms were measured. Flexor carpi radialis and flexor carpi ulnaris muscles are marked as dashed lines to indicate that they arise from the medial aspect of the humerus and insert medially at the metacarpus and carpus, respectively. The abductor pollicis longus muscle is not shown.

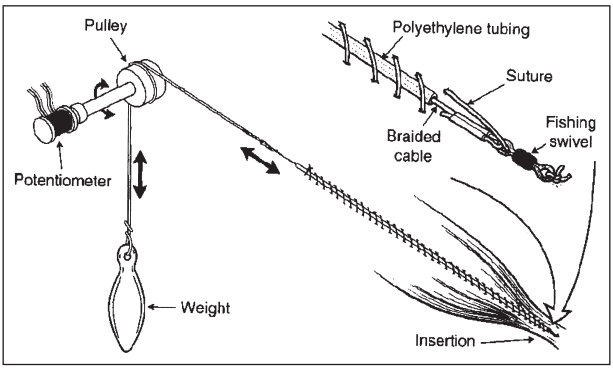

Figure 2—Diagram of a typical tendon connection for 1 muscle of the forelimb of a horse. Muscle-tendon excursions were measured with potentiometers during leg motion. Muscle-tendon units were loaded with a 1.83-kg weight to maintain tension (force of 18 N) and overcome friction.

axis of the digit, was withdrawn from the metacarpophalangeal joint but was allowed to remain in the digit to maintain fixation of the interphalangeal joints. A transarticular Steinman pin was placed longitudinally through the carpus while tendon excursions about the metacarpophalangeal joint were measured. The pin entered the craniolateral aspect of the third metacarpal bone 3 to 5 cm distal to the carpometacarpal joint line, passed centrally through the distal and proximal rows of carpal bones, and exited the caudomedial aspect of the radius 3 to 5 cm proximal to the radiocarpal joint line.

The carpal joint was flexed (180° to 70°) and extended (70° to 180°) for 50 seconds (approx 15 cycles), and the joint angle was measured with a potentiometer aligned with the approximate center of rotation.[16] The carpal joint was treated as a single joint complex rather than distinct radiocarpal and intercarpal joints. To align the potentiometer, the joint was rotated through its range of motion, and position of the potentiometer's axis was adjusted until it was aligned with a functional axis for that joint.[11,17] This axis was defined by a line that passed through 1 location on the medial and 1 location on the lateral surface of the joint that translated least during joint rotation.

The potentiometer was similarly aligned with the metacarpophalangeal joint axis of rotation[16,18] as the joint was flexed and extended between 180° and 110°. The same investigator (NATB) manually performed passive movements of the carpal and metacarpophalangeal joints. The joints were rotated from 180° to flexed positions at which marked soft-tissue resistance to further rotation was evident.

Extension of the metacarpophalangeal joint was achieved with an independent loading frame (**Fig 4**). Two 10-mm steel rods were placed through holes drilled through the third metacarpal bone and loading frame. The rods were stabilized with eyebolts fixed to the loading frame. A cable was attached through a hole drilled in the hoof and distal phalanx. A pulley system (mechanical advantage, 4:1) and ratcheted crank were used to draw the metacarpophalangeal joint into approximately 220° of extension. Three complete extension-flexion cycles (from 180° to approx 220° and back to 180°) were performed on the joint during 8 × 50-second sampling periods.

Only flexion-extension moment arms were measured for muscles that cross the carpal and metacarpophalangeal joints. Muscles that cross the carpal and metacarpophalangeal joints are likely to have moment arms for out-of-plane motion (abduction-adduction and internal-external rotation), but these movements are small during in vitro loading.[19] It was assumed in our study that the primary motion, and therefore primary moment arms, was in the plane associated with joint flexion and extension.

Moment arms were calculated by use of the tendon-excursion method summarized by An et al[6] and Pandy.[10] Perhaps the most notable advantage of the tendon-excursion method is that it does not require knowledge of a joint's center of rotation or the line of action of the muscle. Furthermore, the derivative of muscle length with respect to joint angle in revolute joints is equal to the shortest distance from the axis of rotation to the line of action of the muscle (ie, the moment arm of the muscle).[10] The moment arm is equal to the slope of the curve defined by the change in muscle length versus change in joint angle and is calculated by the following equation:

$$\text{moment arm} = \frac{dL^{M}}{d\theta}$$

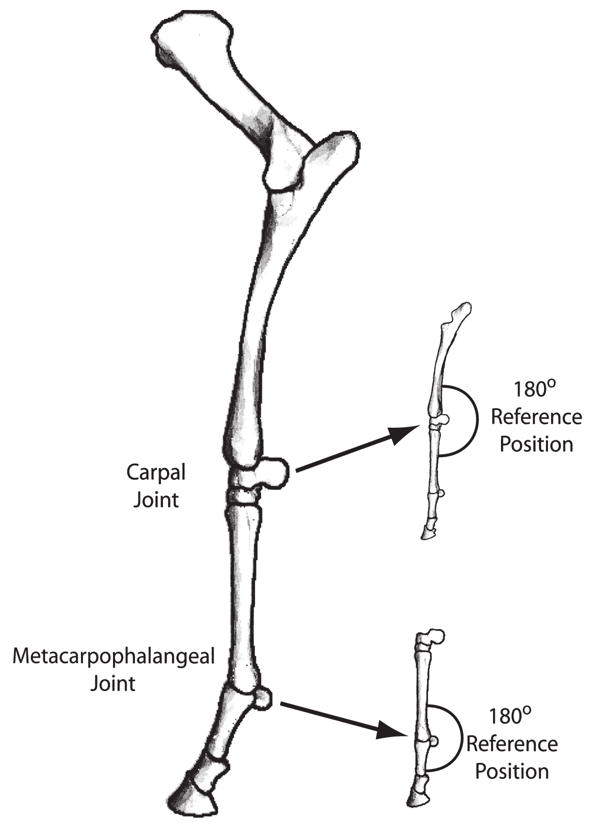

Figure 3—Illustration of the lateral aspect of the forelimb of a horse. Carpal and metacarpophalangeal joint angles were defined on the caudal aspect of each joint. The reference joint angle of 180° is indicated and is equivalent to the position at which all bones are aligned with the long axis of the limb.

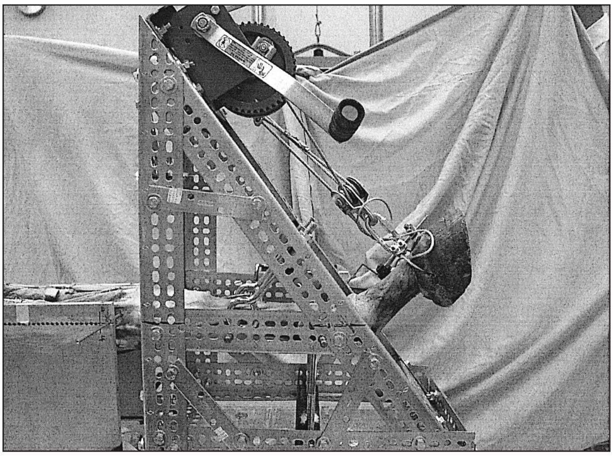

Figure 4—Photograph of a cadaveric forelimb of a horse positioned on a custom-built loading frame used to extend the metacarpophalangeal joint of the limb to approximately 220°.

Table 1—Characteristics of 2 horses from which 4 cadaveric forelimbs were obtained for use in muscle moment arm experiments

	Length (m)	
Horse forelimb	**Third metacarpal bone**	**Ulna and radius**
Horse 1 left	0.27	0.36
Horse 1 right	0.28	0.37
Horse 2 left	0.29	0.45
Horse 2 right	0.29	0.47

Other variables included body weight (horse 1, 410 kg; horse 2, 500 kg), age (horse 1, 3 years; horse 2, 9 years), and height (horse 1, 1.4 m; horse 2, 1.6 m). Height recorded was height at the top of the shoulders. Length of the third metacarpal bone and antebrachium was measured on the cranial surface from the proximal to distal margins of each bone.

Table 2—Range of muscle moment arms obtained from tendon-excursion measurements made on 4 cadaveric forelimbs from 2 horses

Muscle	Horse 1		Horse 2		Peak ratio	Scaled ratio
	Min	Max	Min	Max	Horse 2 : Horse 1	Horse 2 : Horse 1
Superficial digital flexor	14.9	31.2	28.9	43.9	1.41	1.12
Deep digital flexor	17.2	30.9	21.6	35.5	1.15	0.91
Common digital flexor	–12.2	–2.2	–17.6	–1.3	1.44	1.14
Lateral digital flexor	–9.0	0.0	–14.1	–1.2	1.56	1.24
Ulnaris lateralis	11.4	26.9	13.0	33.5	1.25	0.99
Extensor carpi radialis	–25.0	–7.1	–31.9	–19.3	1.28	1.01
Flexor carpi radialis	12.7	25.8	7.6	34.9	1.35	1.07
Flexor carpi ulnaris	20.5	29.2	11.2	45.0	1.54	1.22
Abductor pollicis longus	–3.3	0.5	–8.2	0.7	2.48	1.97
Mean of ratios					1.50	1.19

Maximum (Max) and minimum (Min) values represent mean moment arms obtained from left and right limbs of each horse. Peak ratio is the ratio of peak moment arm magnitudes (absolute value) of each muscle from horse 2 versus horse 1. Scaled ratio is the ratio between limbs of peak moment arm magnitude from each muscle divided by the antebrachium length from that limb for horse 1 versus horse 2. Values for the deep digital flexor, common digital extensor, and flexor carpi ulnaris muscles are for their humeral heads.

where L^M is the length (in meters) of the muscle, and θ is the joint angle (in radians).

Voltage data from the joint angle potentiometer and single-turn precision potentiometers were recorded at 20 Hz with data acquisition software.[c] Each 10-second sample was separated into individual sweeps by use of potentiometer peaks in the joint angle output. These sweeps were further separated in flexion and extension phases. All voltages were converted to muscle length and joint angle by use of scaling factors determined from calibration experiments. A 5-point, sliding-window average was used to smooth muscle length and joint angle data.[11]

Results

Tendon excursions and joint angles during flexion and extension of the carpal and metacarpophalangeal joints were measured in 4 fresh-frozen forelimbs obtained from 2 Thoroughbreds **(Table 1)**. Peak moment arms about the carpal and metacarpophalangeal joints were a mean of 1.5 times greater in horse 2 than in horse 1 **(Table 2)**. However, horse 2 was 1.22 times heavier and 1.14 times taller than horse 1. When moment arm magnitudes were scaled to the length of the antebrachium, peak moment arm magnitudes were only 1.19 times greater in horse 2, compared with values for horse 1. Data that follow are an average of data from the 4 limbs tested.

Moment arms for muscles that flex the carpal joint (ie, those that pass on the caudal aspect of the joint) did not differ greatly in magnitude in the first 30° of carpal flexion **(Fig 5)**. In this range of motion (180° through 150°), peak moment arm magnitudes were between 30 and 31 mm for the ulnaris lateralis, flexor carpi radialis, and deep digital flexor muscles. Flexor carpi ulnaris and superficial digital flexor muscles had mean peak moment arms of 35.6 and 37.2 mm, respectively. Between 180° and 150° of carpal flexion, changes in carpal flexor moment arms were < 5.1 mm **(Table 3)**.

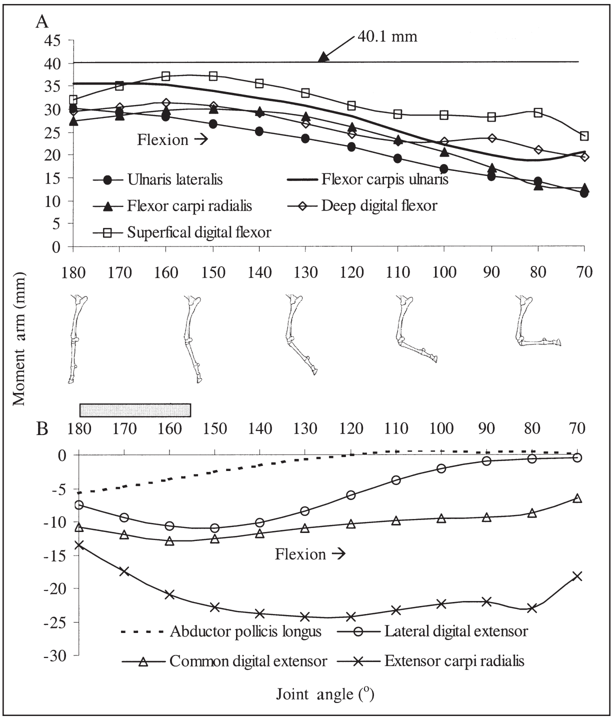

Figure 5—Values obtained during carpal flexion for moment arms of the flexor (A) and extensor (B) muscles that cross the equine carpal joint. Data represent mean values of 4 forelimbs. Shaded box indicates range of motion of the carpal joint during the stance phase of walking and trotting.[1,3,5] Horizontal line represents the flexor moment arm (40.1 mm) used by Meershoek et al[7] to predict muscle forces in the superficial and deep digital flexor muscles.

The carpal joint moment arm for the extensor carpi radialis muscle increased from 13.5 mm at 180° of carpal flexion to a peak magnitude of 24.3 mm at 130° of carpal flexion (Fig 5). During the first 30° of carpal flexion, the moment arms of the extensor carpi radialis, lateral digital extensor, and common digital extensor muscles changed by 41, 32, and 15%, respectively. The magnitudes of these changes were < 3.5 mm for the common and lateral digital extensor muscles and 9.3 mm for the extensor carpi radialis muscle. The abductor pollicis longus muscle had a small moment arm (< 6 mm) that approached 0 when the carpal joint was flexed > 130°.

At 190° of metacarpophalangeal joint extension, the superficial digital flexor and deep digital flexor muscles had peak flexor moment arms of 32.9 and 34.2 mm, respectively **(Fig 6)**. The changes in moment

Table 3—Changes in magnitude of muscle moment arms within the range of motion associated with the stance phase of the gait

Muscle	Carpal 180° to 150° (mm [%])	Metacarpophalangeal 220° to 180° (mm [%])
Ulnaris lateralis	3.3 (11.0)	NA
Flexor carpus ulnaris	1.6 (4.4)	NA
Flexor carpi radialis	2.6 (8.6)	NA
Deep digital flexor	1.7 (5.4)	13.1 (38.2)
Superficial digital flexor	5.1 (13.7)	6.8 (20.8)
Abductor pollicis longus	3.2 (55.7)	NA
Lateral digital flexor	3.5 (32.1)	7.4 (99.1)
Common digital extensor	2.0 (15.3)	8.9 (99.1)
Extensor carpi radialis	9.3 (41.0)	NA

Differences between maximum and minimum moment arm values were determined for the metacarpophalangeal joint between 220° and 180° degrees and for the carpal joint between 180° and 150°. Values for the deep digital flexor, common digital extensor, and flexor carpi ulnaris muscles are for their humeral heads.

NA = Not applicable.

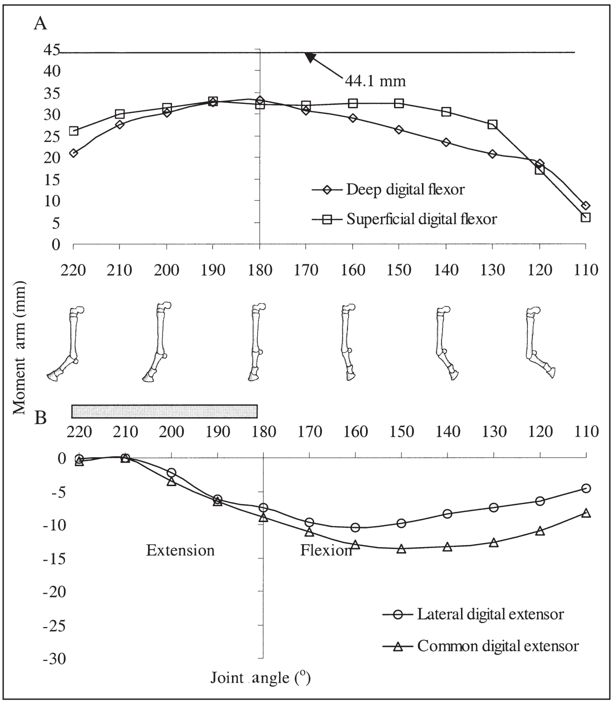

Figure 6—Values obtained during extension and flexion of the metacarpophalangeal joint for moment arms of the flexor (A) and extensor (B) muscles that cross the equine metacarpophalangeal joint. Data were combined for forced extension (180° to 200°) and manual flexion (180° to 110°) experiments. Shaded box indicates range of motion of the metacarpophalangeal joint during the stance phase of walking and trotting.[1,3,5] Horizontal line represents the flexor moment arm (44.1 mm) used by Meershoek et al[7] to predict muscle forces in the superficial and deep digital flexor muscles.

arm magnitudes during metacarpophalangeal joint extension (180° to 220°) were 21% (6.8 mm) and 38% (12.0 mm) for the superficial digital flexor and deep digital flexor muscles, respectively. As the metacarpophalangeal joint was flexed to 110°, flexor muscle moment arms decreased dramatically to < 15 mm.

The extensor muscle moment arms about the metacarpophalangeal joint were smaller than the flexor muscle moment arms. Peak moment arm magnitudes for the lateral digital extensor and common digital extensor muscles were 10.5 and 13.7 mm, respectively, when the metacarpophalangeal joint was positioned near 150° (Fig 6), and varied markedly with respect to joint angle (Table 3). These values became small during metacarpophalangeal joint extension (Fig 6), indicating that the common digital extensor and lateral digital extensor muscles have little capacity to extend the digit about the metacarpophalangeal joint during the range of motion evident during various phases of the gait in horses.

Discussion

Determination of muscle moment arms provides insight into muscle function and allows development and validation of musculoskeletal models of equine forelimbs. These functional insights, together with the development of detailed musculoskeletal models, may provide increased understanding of musculotendinous and articular joint injuries in horses. The purpose of the study reported here was to examine whether moment arms of the muscles around the carpal and metacarpophalangeal joints remain constant over the joint angles observed during the stance phase of the gait. The moment arms at the carpal joint for the extensor carpi radialis, common digital extensor, and lateral digital extensor muscles varied ≤ 9 mm over the range of joint positions reported for various phases of the gait in horses.[1,3,5] Similarly, between 180° and 220° of metacarpophalangeal joint extension (ie, range of motion detected during the stance phase of the gait), moment arms for the superficial digital flexor and deep digital flexor muscles varied by 7 and 13 mm, respectively. Together, these findings do not support the assumption that extensor moment arms about the carpal joint and both flexor and extensor moment arms about the metacarpophalangeal joint can be modeled as fixed-radius pulleys.[7,13,14]

Certain limitations were associated with the study reported here. To represent muscle paths, wire cables were sutured to the superficial aspect of the musculotendinous junction and passed across the surface of muscles and through origins represented by single locations. This representation of muscle path is often used in biomechanical studies, although it is clear that muscles do not have discrete origins, and their paths are not single lines. To reduce the impact of these assumptions, the anatomic relationship of muscles was preserved in situ, and eyelets were placed at the centroid of each muscle's origin. Even with these methods in place, there may have been an offset in moment arm magnitudes, but this potential offset should be consistent across the range of motion of each joint.

Because of a limitation of the loading frame, the metacarpophalangeal joint was extended only to 220°, although the range of motion of the gait during galloping exceeds this value.[20] Hydraulic presses have been used to force metacarpophalangeal joint extension farther, but ensuring rigid fixation of the interphalangeal, carpal, and elbow joints in this configuration would have been problematic. To accurately calculate moment arms by use of the tendon-excursion method, all joints that are not being tested must be rigidly fixed. Another alternative was to cut the suspensory ligament. This would have allowed greater metacarpophalangeal joint extension with minimal loading, but the catastrophic effect on metacarpophalangeal joint biomechanics excluded this as a possibility. Indeed, it would be interesting to determine whether the moment arms of superficial and deep digital flexor muscles continue to decrease with greater metacarpophalangeal joint extension, as extrapolation of our data suggests.

Experimental error was low for measurements of tendon excursion, joint angle, and moment arm magnitude (0.41 mm for the acrylic plastic model). This small experimental error was unlikely to influence the interpretation of results, because moment arm magnitudes exceeded the experimental error by an order of magnitude. The only exception was the muscle moment arm for the abductor pollicis longus muscle. Between 130° and 70° of carpal flexion, the muscle moment arm magnitude for the abductor pollicis longus muscle was < 0.7 mm and changed from negative (extensor) to positive (flexor) values. Because experimental error was of the same order of magnitude as the moment arms of the abductor pollicis longus muscle, this results should not be interpreted as a change in muscle function; instead, it indicates that the flexion-extension moment arm for the abductor pollicis longus muscle is approximately 0 when the carpal joint is flexed to > 130°.

Differences in moment arm magnitudes were observed between the 2 horses used in this study. This difference was probably a consequence of size; results from another study[7] indicate large moment arm magnitudes in large horses. In reporting our data, mean values were used to illustrate the changes in moment arm magnitudes with respect to joint angle. Furthermore, we expect that animals of differing size or various breeds would have moment arms of differing magnitudes. However, assuming that carpal and metacarpophalangeal joint kinematics (ie, location of the center of rotation) and the tendon passage for these joints do not vary greatly among breeds, moment arms would likely vary with respect to joint angle in a manner similar to that indicated by the data reported here.

Tendon excursion measurement is also limited when tendons are strongly bound to underlying bone at intermediate points located between the muscle's origin and the joint being examined. On rotation of the joint, there may be a greater change in tendon length in the portion of the tendon distal to the intermediate point than in the portion of the tendon proximal to this point. For example, the inferior check ligament of the deep digital flexor muscle arises midway in the metacarpus, creating an intermediate binding point. As a result, extension of the metacarpophalangeal joint may change the length of the tendon distal to the check ligament more than that of the proximal portion of the tendon. Because changes in tendon length were detected by use of wire cable that was sutured to the proximal part of the tendon, the measured change in length of the deep digital flexor tendon may have been underestimated during metacarpophalangeal joint extension. In contrast, the superficial digital flexor tendon is bound proximally (superior check ligament), and the excursion of the cable sutured to the proximal tendon would be less affected. Indeed, there is a slight decrease in the moment arm magnitude of the deep digital flexor muscle, compared with the superficial digital flexor muscle.

Muscle moment arms can provide insight into function of equine forelimbs during various gaits. For example, moment arms of the small lateral and common digital extensor muscle arms during metacarpophalangeal joint extension indicate that these muscles can do little to rotate the metacarpophalangeal joint into extension. Because results of other studies[1,2,4] indicate that the joint moment of the metacarpophalangeal joint muscle remains flexor throughout the stance phase of the gait, our finding suggests that during walking and trotting, metacarpophalangeal joint extension is a result of passive (nonmuscular) forces that are most likely generated by body weight.

Flexor moment arms about the carpal joint were found to be larger than extensor moment arms, a finding that also provides insight into function of equine forelimbs. The carpal joint remains near full extension during the stance phase of the gait; through alignment of the radius with the metacarpus and carpus, passive-structural joint stability is promoted, and the need for large moment arms of the extensor muscles is minimized. In support of this idea, the muscle moment about the carpal joint during the stance phase is a flexor moment.[1,2,4] The carpal joint also undergoes considerable flexion and extension during the swing phase, an action that is facilitated and controlled by the carpal flexor and extensor muscles. For example, rapid extension of the metacarpus during late swing is a result of the combined effect of large extensor muscles with large moment arms and induced accelerations arising from adjoining segmental motion. The muscle moment arm of the extensor carpi radialis muscle was largest of all the carpal extensors when this joint was flexed; the suggestion that this muscle assists in limb extension during the late part of the swing phase is supported by electromyographic data that indicate the extensor carpi radialis muscle is active during the second half of the swing phase of walking.[21]

Variation in moment arm magnitudes with respect to joint angle can also be explained in terms of the functional anatomy of the forelimb. At the metacarpophalangeal joint, the superficial and deep digital muscle tendons are held close to the palmar aspect of the third metacarpal bone by connective tissue (eg, digital synovial sheath[22]); therefore, the horizontal (approx perpendicular) distance between the digital flexor tendons and center of rotation of the metacarpophalangeal joint is small when the joint is flexed. As the metacarpophalangeal joint extends, the proximal sesamoid bones rotate about the large condyles of the distal metacarpus and force the tendons farther from the joint center. With greater joint extension, the proximal sesamoids slide beneath the distal aspect of the third metacarpal bone; this action reduces the distance between the digital flexor tendons and the center of rotation of the metacarpophalangeal joint.

Moment arms of muscles in equine forelimbs have been reported[13,14] and used to estimate muscle forces.[7] Using geometric methods, Meershoek et al[7] reported that moment arms for the superficial and deep digital flexor muscles at the metacarpophalangeal joint are constant and equal to 52.5 and 44.1 mm, respectively. Although these magnitudes are similar to those found in our study, our data indicated that the magnitude of these moment arms varies greatly across joint angle (up to 13 mm).

To further illustrate the importance of changes in moment arm magnitudes with respect to joint angle, the force in a muscle can be estimated from the relationship between musculotendinous force, its moment arm, and a muscle moment, whereby the muscle moment is equal to the musculotendinous force multiplied by the moment arm. As reported by Meershoek et al,[7,23] the deep digital flexor muscle appears to bear approximately 22% of the peak flexor muscle muscle moment of the metacarpophalangeal joint during the stance phase. This peak moment is evident at approximately 45% into the stance phase during trotting and has a magnitude of approximately 750 Nm for a 500-kg horse.[1] When we apply the maximal value of 34.2 mm for the moment arm of the deep digital flexor muscle determined in our study, the force in the deep digital flexor muscle would be 4,825 N. In our study, a decrease in the deep digital flexor muscle moment arm of 9.1 mm was detected between 200° and 220° of metacarpophalangeal joint extension. This decrease in moment arm magnitude would increase force of the deep digital flexor muscle to 6,574 N (an increase of 36%). Clearly, this simplified example reveals that assumptions for muscle moment arm magnitudes with respect to joint angle can considerably affect the estimation of muscle force.

Results of the study reported here were related to the normal ranges of motion reported for the carpal and metacarpophalangeal joints during walking and trotting,[1,3,5] because these are the ranges of motion in which muscles in equine forelimbs bear the greatest loads. Moreover, in a musculoskeletal model of the equine forelimb that is used to predict muscle forces during various phases of the gait, these are the joint positions for which muscle force predictions (dependent on moment arms) would be made. Also, musculoskeletal models used to predict muscle forces rely heavily on accurate musculoskeletal geometry (ie, muscle moment arms). Empirically measured moment arms can be used to compare similar values determined from these models to assess the models' accuracy.[24-27] Our data regarding moment arms of the carpal and metacarpophalangeal joints of equine forelimbs will provide a means of developing and assessing musculoskeletal models to further study muscle, ligament, and joint injuries in the forelimbs of horses.

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[a] van den Bogert AJ, Schamhardt HC, Sauren AAHJ, et al. Computer simulation of equine locomotion and its application to the study of force distribution in the limbs. *Computer simulation of locomotion in the horse*. PhD dissertation, Technische Universiteit Eindhoven, 1989;111–136.

[b] Courtesy of Dr. J. Edwards, Department of Pathobiology, College of Veterinary Medicine, Texas A&M University, College Station, Tex.

[c] Labview, National Instruments Inc, Austin, Tex.

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