Effect of water depth on amount of flexion and extension of joints of the distal aspects of the limbs in healthy horses walking on an underwater treadmill

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Objective—To determine the maximum amount of flexion and extension of the carpal, tarsal, metacarpophalangeal, and metatarsophalangeal joints and the percentage duration of the stance and swing phases of the stride for horses walking on an underwater treadmill in various water depths.

Animals—9 healthy adult horses.

Procedures—Zinc oxide markers were placed on the forelimbs and hind limbs of the horses. Video was recorded of horses walking (0.9 m/s) on an underwater treadmill during baseline conditions (< 1 cm of water) or in various amounts of water (level of the metatarsophalangeal, tarsal, and stifle joints). Maximum amount of joint flexion and extension, range of motion (ROM), and the percentage durations of the stance and swing phases of the stride were determined with 2-D motion analysis software.

Results—The ROM was greater for all evaluated joints in any amount of water versus ROM for joints in baseline conditions (primarily because of increases in amount of joint flexion). The greatest ROM for carpal joints was detected in a tarsal joint water depth, for tarsal joints in a stifle joint water depth, and for metacarpophalangeal and metatarsophalangeal joints in metatarsophalangeal and tarsal joint water depths. As water depth increased, the percentage durations of the stance and swing phases of the stride significantly decreased and increased, respectively.

Conclusions and Clinical Relevance—Results of this study suggested that exercise on an underwater treadmill is useful for increasing the ROM of various joints of horses during rehabilitation and that the depth of water affects the amount of flexion and extension of joints. (*Am J Vet Res* 2013;74:557–566)

Aquatic exercise is an established rehabilitation method for humans,[1–4] small animals,[5,6] and horses.[7–9] Because of the physical properties of water (eg, buoyancy, viscosity, resistance, hydrostatic pressure, and surface tension), such exercise may be beneficial for animals in rehabilitation programs.[10] Water can decrease the amount of weight placed on joints, exert constant pressure on submerged portions of the body or limbs, and aid in venous and lymphatic drainage of tissues. During exercise in water, perception of pain may be decreased because of phasic stimulation of sensory receptors; in addition, muscle strength and cardiovascular fitness may be improved.[11–14] Other authors have suggested that aquatic rehabilitation may allow humans[15] and small animals[16,17] with orthopedic problems early use of limbs after injury or surgery and may help minimize the risk of reinjury.

Swimming is a common conditioning method for noninjured equine athletes[18] and has been used as a rehabilitation method for horses with musculoskeletal injuries.[19] However, swimming is considered a high-intensity activity for horses; during swimming, horses may have heart rates > 200 beats/min.[13] Such high-intensity exercise is not ideal for horses with orthopedic problems immediately after injury or surgery or during a period of prolonged rest. Underwater treadmills can be used as an alternative to swimming for exercise of horses; such exercise is beneficial for humans with limb injuries.[20] Many horse training centers and veterinary

Abbreviation

ROM	Range of motion

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hospitals have underwater treadmills available for exercise of horses. Use of underwater treadmills presumably has some of the benefits of swimming for horses, such as reduction of concussive forces on distal aspects of limbs and aerobic exercise during the early period of rehabilitation; horses exercising on underwater treadmills have heart rates up to 78 beats/min during walking[21] and 120 beats/min during trotting.[14]

The goal of a musculoskeletal rehabilitation program is to restore limb function via maximizing flexibility of injured soft tissues, increasing muscle and bone strength, and reestablishing biomechanically normal ROM of affected joints.[22] Results of other studies[1,23] indicate passive or active flexion and extension of injured limbs early during a rehabilitation period is important for a good outcome for humans recovering from orthopedic injury or surgery.[1,23] Aquatic rehabilitation improves postoperative limb function and ROM in dogs[24,25] and humans.[1,26] However, to the authors' knowledge, information has not been published regarding the effects of aquatic rehabilitation on ROM of joints of the distal aspects of limbs in horses.

Information regarding the effects of underwater treadmill exercise and treadmill water depth on ROM of joints of distal aspects of limbs of horses would be useful for clinicians and physical therapists who design rehabilitation programs for horses. Therefore, the objectives of the study reported here were to determine the maximum flexion and extension angles and ROM of the carpal, tarsal, and metacarpophalangeal and metatarsophalangeal (ie, forelimb and hind limb fetlock) joints of horses at 4 water depths (< 1 cm [baseline] and at the level of the hind limb fetlock, tarsal, and stifle joints); the percentage duration of the stance and swing phases of the stride at those water depths; and the water depth at which the greatest flexion and extension of each joint is detected. We hypothesized that the ROM of the joints of the distal aspects of the limbs would increase during walking of horses on an underwater treadmill at any depth of water, compared with baseline conditions. Additionally, we hypothesized that the amount of joint flexion and extension and the percentage duration of the swing phase of the stride during walking would increase with increasing treadmill water depth.

Materials and Methods

Horses—Nine horses (8 Quarter Horses and 1 Thoroughbred; mean ± SD age, 8.1 ± 4.3 years; mean ± SD body weight, 486.6 ± 26.3 kg; mean ± SD height at the shoulders [withers], 150.1 ± 3.2 cm) owned by our research laboratory at the University of Minnesota were included in the study. Before horses were enrolled in the study, thorough physical and lameness examinations were performed. Results of these examinations were unremarkable for all of the horses. The study was approved by the University of Minnesota Institutional Animal Care and Use Committee.

Underwater treadmill training—All horses included in this study had previous experience with exercise on a standard treadmill. Horses have a consistent gait after 4 to 6 sessions of water treadmill exercise[27]; therefore, horses in the present study were walked on an underwater treadmill[a] during 6 training sessions (30 min/session) before data were collected. Xylazine[b] (0.2 mg/kg, IV) was administered for the first 2 training sessions if horses developed signs of anxiety or were reluctant to walk on the underwater treadmill. Horses initially walked on the treadmill in < 1 cm of water (baseline conditions; the minimum amount of water required for operation of the treadmill) to allow acclimatization. During the subsequent training sessions, horses were acclimatized to walking on the underwater treadmill in various depths of water (water at the level of the hind limb fetlock, tarsal, and stifle joints). The speed of the treadmill was maintained at 0.9 m/s during training sessions and data collection. Water temperature was not controlled (water temperature range during the study, 15° to 21°C).

Kinematic measurement procedure—For detection of movement of distal aspects of limbs under water, zinc oxide was applied to the skin on limbs of horses because it does not readily dissolve in water. Four zinc oxide markers (diameter, 2 cm) were placed on the left forelimb and left hind limb of each horse; these were the only limbs that could be observed through the treadmill windows (**Figure 1**). Markers were placed on the lateral aspects of each limb, at the center of rotation of each joint. For each horse, forelimb markers were placed at the level of proximal interphalangeal joint, lateral condyle of the distal aspect of the third metacarpal bone, ulnar carpal bone, and 15 cm proximal to the ulnar carpal bone on the groove between the common and lateral digital extensor muscles **(Figure 2)**. Hind limb markers were placed at the level of proximal interphalangeal joint, lateral condyle of the distal aspect of the third metatarsal bone, middle aspect of the talus, and 10 cm proximal to the tuber calcanei on the groove between the long and lateral digital extensor muscles. Locations of the skin markers were chosen on the basis of other authors' recommendations,[28] with slight modifications because of the size of the windows of the underwater treadmill. The most distal markers were placed at the level of the proximal interphalan-

Figure 1—Photographic image of a horse walking on an underwater treadmill in water up to the level of the stifle joints. A digital video camera can be seen on the left side of the image (white arrow) in a position for recording of the left forelimb through the front window of the treadmill. Illumination is provided by a 300-W halogen lamp positioned close to the window at an approximately 45° angle so that light reflections are not visible in the video images.

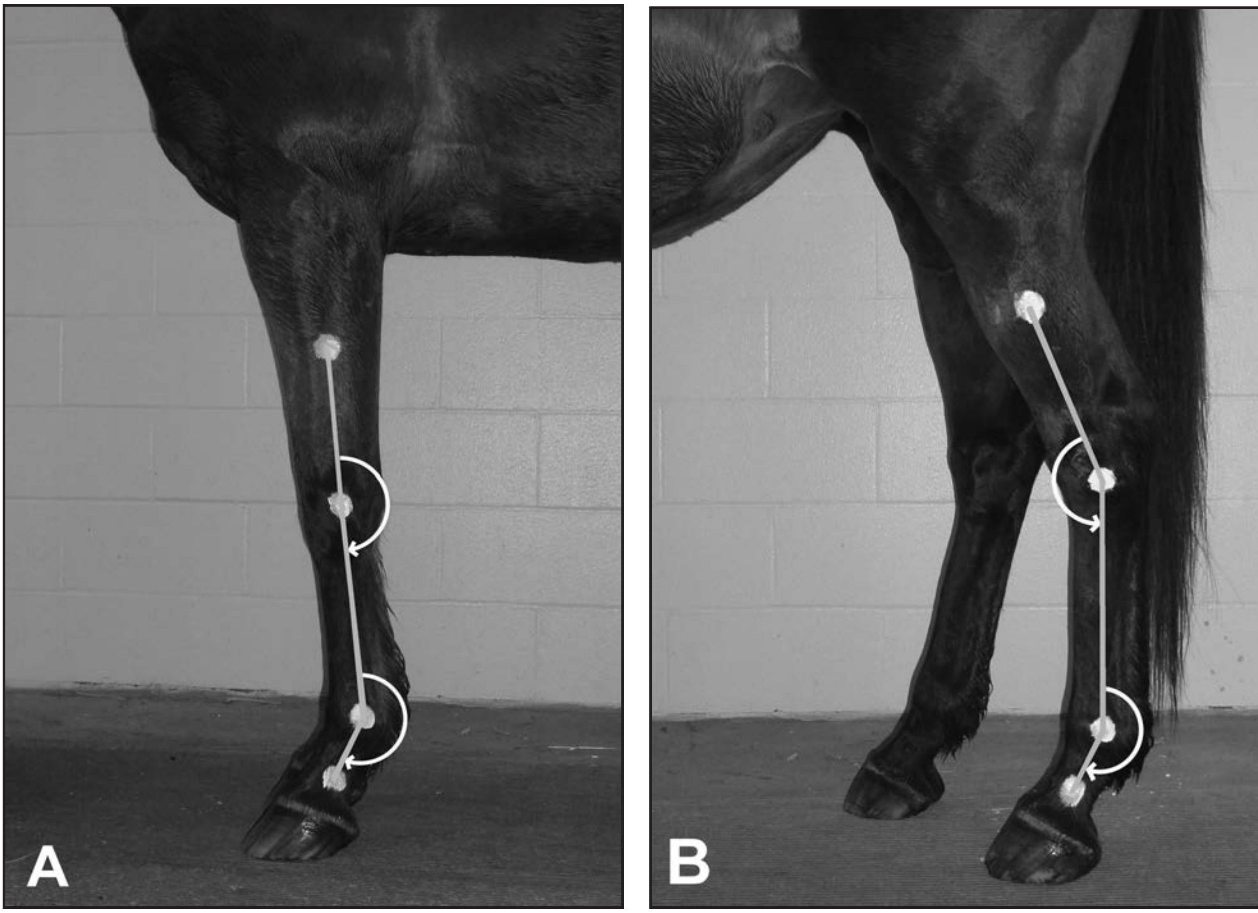

Figure 2—Photographic images of a horse indicating the locations of forelimb (A) and hind limb (B) skin markers (white circles) used to identify body segments (light gray lines) for determination of joint angles. Measurements of angles for each evaluated joint (carpal, tarsal, and metacarpophalangeal and metatarsophalangeal [forelimb and hind limb fetlock]) are indicated (curved white arrows).

geal joint instead of the hoof, and the most proximal markers were placed in the middle aspect of the tibia or radius instead of the proximal aspects of those bones so that markers would be visible during all phases of the stride and at all evaluated water depths. Hair was clipped from limbs at these locations to ensure consistency of marker placement.

Two-dimensional movement was recorded with a digital video camera[c] (6.0-mm lens) recording 60 frames/s while horses were walked on the underwater treadmill at each of the 4 evaluated water depths (< 1 cm of water [baseline depth] and water to the level of the hind limb fetlock, tarsal, and stifle joints). For the fetlock joint water depth, the underwater treadmill was filled with water up to the level of the skin marker on the lateral condyle of the distal aspect of the third metatarsus. For the tarsal joint water depth, the underwater treadmill was filled with water up to the level of the skin marker on the middle aspect of the talus. For the stifle joint water depth, the underwater treadmill was filled with water up to the level of the tibial plateau (determined via manual palpation). Videos were recorded from the left side of the underwater treadmill through 1 of the 2 transparent plastic windows (Figures 1 and 3). For each horse, video was recorded during 2 sessions on different days (1 session for forelimb videos and 1 session for hind limb videos). Before each video recording session, feces were manually evacuated from the rectum of each horse (to minimize risk of contamination of water with feces, which could have obscured skin markers). During the first video recording session for each horse, the digital video camera was positioned on a tripod 152 cm above the floor and 140 cm away from the middle aspect of the front window of the underwater treadmill; this allowed video recording of left forelimbs. Because of the small size of the window (90 × 70 cm), the camera was angled (30° below horizontal) so that the most distal skin markers at the level of the proximal interphalangeal joints would be recorded. Skin markers were illuminated by a 300-W halogen lamp positioned close to the window (placed at an approx 45° angle so that light reflections were not visible in the video). For each water depth, horses were acclimatized on the treadmill for 5 minutes, then 10 continuous complete strides of the left forelimb at a walk were recorded; this was repeated for each evaluated water depth. During the second session, the same procedures were used to record movement of hind limbs of horses through the rear window (90 × 70 cm) of the underwater treadmill; during the second session, placement of the video camera and light relative to the rear window were identical to their placement relative to the front window during the first session. Video recording for each horse was completed within approximately 30 minutes during each video recording session to prevent changes in gait attributable to fatigue.

Two-dimensional kinematic analysis was performed with a gait analysis system.[d] Software calibration was performed at the beginning of each session by the use of a known distance marked on each window of the underwater treadmill. One stride for a limb was defined as the cycle between complete (heel and toe) foot contact with the treadmill belt and the subsequent complete foot contact of that same foot with the treadmill belt. For a stride, stance phase duration was determined via counting the number of video frames in which the foot contacted the belt (from the time the heel of the foot contacted the belt to the time of foot breakover [ie, loss of contact of the toe with the belt]). The duration of stance and swing phases of the forelimb and hind limb strides were calculated for each horse for each water depth. The 10 continuous videotaped strides were reviewed; the 5 strides with the least amount of water movement (ie, splashing) and best visibility of skin markers were used for tracking and calculation of stride duration percentages. Skin markers were tracked via a combination of automated and manual methods to identify body segments that represented joints and distal aspects of limbs. Each frame of each stride was manually reviewed by one of the investigators (JLMA); during review, limb markers on videos were magnified to ensure that the center of each marker was appropriately selected. The center of each marker was selected manually in all frames in which the software did not appropriately select them; approximately 90% of markers were selected manually, and 10% were correctly selected with the software. For each complete stride, maximum flexion and extension angles of each joint of interest were calculated on the basis of the rotation of the proximal and distal body segments around the palmar and plantar (carpal and fetlock joints) and dorsal (tarsal joints) aspects of the joints via an inverse tangent function (Figure 2). The ROM of the evaluated joints, represented by the relative intersegmental motion, was calculated for each stride of each horse at each water depth (maximum extension angle minus the maximum flexion angle).

Figure 3—Photographic image of a horse on an underwater treadmill in water up to the level of the stifle joints. This image was acquired with the camera that was used to obtain videos of horses in the study. Notice that the skin markers on the left forelimb are easily seen.

A post hoc error calculation was performed to correct data for the camera angle and light refraction in water by placing a right angle in the areas of maximum flexion and extension of each evaluated joint (fetlock, carpal, and tarsal joint regions). The right angle had 2-cm-diameter markers on both arms and at the center of rotation. Videos were recorded and data were analyzed by use of the same equipment locations and software that were used during video recording of horses for determination of kinematics. Data were determined for each skin marker location in the treadmill with the baseline amount of water (no markers under water), with markers partially submerged in water (most distal 2 markers in the water and the most proximal marker out of the water), and with all markers submerged in the water; these water depths corresponded to each water depth in which horses had walked on the treadmill during data collection. The treadmill was not moving during these measurements. To determine whether the camera angle caused data error, measurements were repeated with the camera positioned horizontal to the ground. Fifty measurements were determined, and the markers on the right angle were tracked. The error was determined on the basis of the differences of values from 90°, and data were corrected for the mean errors identified at each location and each water depth before statistical analysis.

Statistical analysis—Mean ± SD values of maximum flexion and extension angles, ROM of joints, and percentage duration of stance and swing phases of the stride for each water depth were determined via calculation of the mean value of 5 strides of each horse, and then combining the mean values of all horses at each water level. These calculated values were analyzed via extreme Studentized deviate tests to identify outlier values, which were subsequently removed for further analysis. Stance and swing phase durations were expressed as percentages of the total duration of the stride. Normality of data was assessed via the Shapiro-Wilk normality test. Statistical differences in values among the 4 water depths for each joint of interest were determined via a repeated-measures ANOVA with a Tukey-Kramer multiple comparison test. Values of $P < 0.05$ were considered significant. Statistical analyses were performed with software.[e]

Results

The total amount of error in the 2-D kinematic analysis system used in this study was < 3° (including error attributable to camera positioning and light refraction by water). The amount of error was similar for each camera position (30° downward angle and positioning horizontal to the ground). The amount of error was different for each limb location and water depth. The treadmill window location (portion of the window nearest to the cranial aspect of the horse) where flexion typically occurred for fetlock, carpal, and tarsal joints had angles ≤ 90° (87.6° to 90°) that varied among joints of interest and water levels. The window location (portion of the window nearest to the caudal aspect of the horse) where extension typically occurred for fetlock, carpal, and tarsal joints had angles ≥ 90° (90°

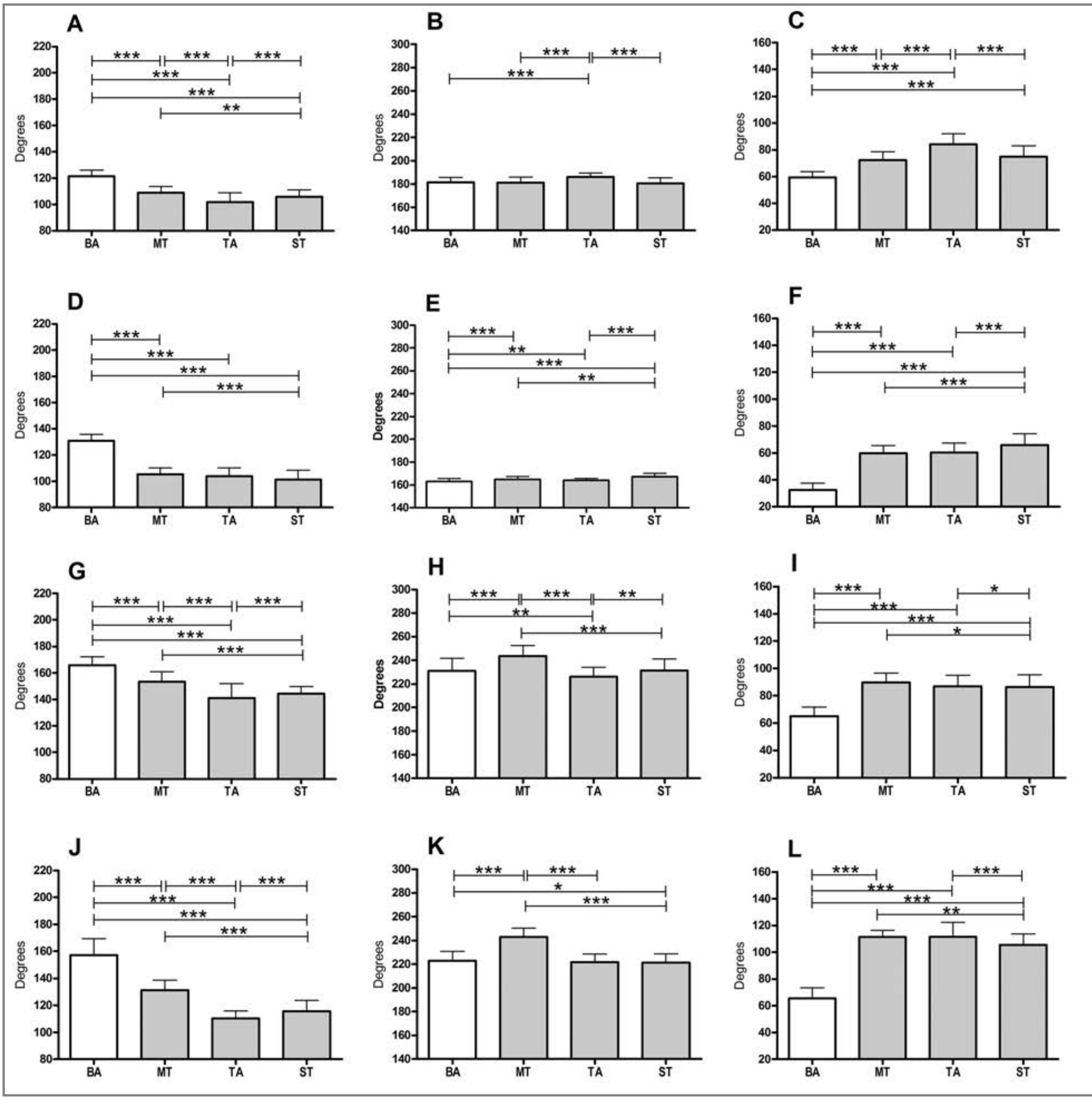

Figure 4—Maximum amount of carpal (A to C), tarsal (D to F), metacarpophalangeal (G to I), and metatarsophalangeal (J to L) joint flexion (A, D, G, and J [left column]) and extension (B, E, H, and K [middle column]) and ROM (C, F, I, and L [right column]) for 9 healthy horses walking on an underwater treadmill in < 1 cm of water (baseline conditions; BA) or water up to the level of the metatarsophalangeal (MT), tarsal (TA), or stifle (ST) joints. Heights of bars represent mean values and error bars represent SD. Horizontal bars with asterisks represent significant (**P* < 0.05; ***P* < 0.01; ****P* < 0.001) differences between data.

to 92.9°) that varied among joints of interest and water levels. For each water depth, the mean errors calculated for each joint during flexion and extension were used to correct the maximum flexion and extension angle values.

Results of kinematic analysis indicated that maximum flexion angles for horses walking in any depth of water (fetlock, tarsal, and stifle joint water depths) in the underwater treadmill were significantly ($P < 0.001$ for all comparisons) higher than those for horses walking during baseline conditions (**Figure 4**). For the 3 depths of water greater than the baseline depth (fetlock, tarsal, and stifle joint water depths), the highest flexion angles for the carpal and forelimb and hind limb fetlock joints were detected in the tarsal joint water depth, and the highest flexion angle for the tarsal joint region was detected in the tarsal and stifle joint water depths (**Table 1**).

The maximum joint extension angle was significantly ($P < 0.001$) higher for carpal joints during walking in the tarsal joint water depth, for tarsal joints during walking in the stifle joint water depth, and for forelimb and hind limb fetlock joints during walking in the fetlock joint water depth, compared with walking during baseline conditions (Figure 4). Conversely, the maximum joint extension angle was significantly ($P < 0.01$) lower for forelimb fetlock joint during walking

Table 1—Mean maximum amount of flexion and extension and ROM for carpal, tarsal, metacarpophalangeal, and metatarsophalangeal joints of 9 healthy horses during walking on an underwater treadmill in various depths of water.

Joint	Water depth	Flexion	Extension	ROM
Carpal	Tarsal joints	20	5	25
Tarsal	Stifle joints	29	4	33
Metacarpophalangeal	Metatarsophalangeal joints	12	13	25
	Tarsal joints	25	–5	20
Metatarsophalangeal	Metatarsophalangeal joints	26	20	46
	Tarsal joints	47	–1	46

Data are degrees.

Data for each joint are indicated for the water depth at which the maximum flexion and extension of the joint (compared with baseline values) were detected.

Table 2—Mean ± SD percentage duration of stance and swing phases of the forelimb and hind limb strides of 9 healthy horses during walking on an underwater treadmill in various depths of water.

	Water depth			
Variable	Baseline (< 1 cm)	Metatarsophalangeal joint	Tarsal joint	Stifle joint
Forelimb				
Stance	67.2 ± 1.9	63.9 ± 1.3	60.0 ± 1.1	57.2 ± 1.0
Swing	32.4 ± 1.7	35.8 ± 1.3	39.9 ± 1.1	42.7 ± 1.0
Hind limb				
Stance	65.6 ± 1.7	62.0 ± 1.4	60.0 ± 2.5	58.2 ± 2.2
Swing	34.3 ± 1.7	37.9 ± 1.4	39.9 ± 2.5	41.8 ± 2.2

Within each row, all values are significantly ($P < 0.01$) different.

in the tarsal joint water depth, compared with walking during baseline conditions. For the 3 evaluated depths of water, the highest extension angle for the carpal joints were detected in the tarsal joint water depth, the highest extension angle for the tarsal joints were detected in the stifle joint water depth, and the highest extension angle of the fetlock joints were detected in the fetlock joint water depth; these values were all significantly ($P < 0.01$) different than values for horses walking in other water levels (Table 1).

The ROM was significantly ($P < 0.001$) greater for all evaluated joints when horses were walking in fetlock, tarsal, and stifle joint water depths, compared with walking during baseline conditions (Figure 4). The highest carpal joint ROM was detected during walking in the tarsal joint water depth and the highest tarsal joint region ROM was detected during walking in the stifle joint water depth. The highest ROM for forelimb and hind limb fetlock joints was detected during walking in the fetlock and tarsal joint water depths (Table 1).

Significant differences were detected in percentage durations of stance and swing phases for forelimb and hind limb strides among all water depths (**Table 2**). As the water depth increased, the percentage duration of the stance phase decreased and the percentage duration of the swing phase increased for forelimbs and hind limbs.

Discussion

Results of the present study indicated that walking of horses in water increases the ROM of the carpal, tarsal, and fetlock joints, primarily because of an increase in the amount of joint flexion; these effects varied with water depth. Additionally, an increase in amount of joint extension was detected in some depths of water. These findings supported our hypothesis that the ROM of joints would increase during walking of horses in water and supported the conclusion of other authors[27] that walking on an underwater treadmill increases joint ROM in horses. Conversely, our hypothesis that joint flexion and extension and the percentage duration of the swing phase of the stride would increase with increasing water depth was not completely supported because joint flexion and extension did not consistently increase with increasing water depth for all evaluated joints.

Clinicians and physical therapists try to increase joint ROM for horses exercising on conventional surfaces via techniques such as passive flexion and extension, walking over poles or cavalettis, and attachment of tactile stimulators or weights to the distal aspects of limbs.[22,29] Some of these techniques have been adapted from rehabilitation techniques used for humans or small animals,[30] and little information is available regarding their effects on joint ROM in horses. Results of 2 recent studies[31,32] indicate that attachment of tactile stimulators and weights (700 g) around the pasterns (ie, region between the coronary band and the fetlock joint) of horses significantly increases flexion of the fetlock, tarsal, and stifle joints during trotting. In contrast, results of other studies[33–35] indicate that the addition of weights to forelimbs of horses does not significantly increase flexion of the carpal or fetlock joints. Results of the present study indicated exercise on a treadmill in various depths of water increased the ROM of all evaluated joints. In addition, at some water depths (stifle and tarsal joint water depths), the increase in the amount of flexion of the tarsal and hind limb fetlock joints (29° and 47°, respectively) was similar or greater than that detected for horses in another study[31] during exercise at a trot with tactile and weighted stimulators applied around hind limb pasterns. Currently, few objective data have been published regarding rehabilitation techniques for horses, and the amount of joint flexion and extension that is beneficial for horses with orthopedic problems during rehabilitation is unknown, to the authors' knowledge. Results of the present study indicated the amount of flexion and extension of joints in horses without lameness during walking in water. Further studies are warranted to determine the effects of exercise on an underwater treadmill for horses with reduced limb ROM. Results of the present study also indicated that walking of horses on an underwater treadmill in various depths of water increased the amount of extension of the evaluated joints; such findings have not been reported for other conventional rehabilitation techniques, to the authors' knowledge. However, the increases in extension of the carpal and tarsal joints of horses detected in this study were ≤ 5°, likely because of the anatomic limits of extension of these joints[36]; determination of the clinical importance of these findings would require further research. Therefore, exercise on an underwater treadmill may have advantages compared with other techniques for early rehabilitation of horses with acute musculoskeletal injuries because such exercise increased flexion and extension of joints in horses in this study. Furthermore, exercise of horses on an underwater treadmill has the additional rehabilitation benefits of water buoyancy, viscosity, resistance, hydrostatic pressure, and surface tension.[9]

Results of kinematic studies of humans and small animals indicate the ROM of joints of the distal aspects of limbs increase during walking in water, compared with walking on land.[37,f] Similar to results of the present study, results of those other studies indicate increases in joint ROM are primarily attributable to increases in joint flexion rather than joint extension. For instance, the amount of ankle and knee joint flexion is greater for humans walking and running in water up to the level of the waist than it is for humans walking or running on land.[37] The amount of flexion of hip, stifle, tarsal, shoulder, and elbow joints is greater for dogs walking on an underwater treadmill than it is for dogs walking on a conventional treadmill.[f] Results of kinematic studies of small animals also indicate that higher water depths do not always cause increased flexion of joints. For instance, the amount of flexion of hip, stifle, and tarsal joints of dogs is greatest when water depth is at the level of the stifle joints, but is lower when water depth is at the level of the greater trochanter of the femur.[38] Results of the present study indicated that the highest amount of flexion of forelimb joints (carpal and fetlock joints) was detected during walking of horses in water at the level of the tarsal joints; this finding may have been attributable to horses elevating limbs out of the water to avoid resistance during movement. This finding was not detected during walking of horses in deep water (ie, stifle joint water depth), potentially because most of the limbs were submerged and horses were unable to lift limbs above the surface of the water; in that water depth, horses had to move their entire forelimbs through the water during locomotion. For hind limbs of horses in this study, the highest amount of flexion of tarsal joints was detected during walking in water at the level of the tarsal and stifle joints. This finding may have been attributable to synchronized movement of the reciprocal apparatus causing simultaneous stifle and tarsal joint flexion or extension.[39] At these water depths (tarsal and stifle joint water depths), horses may have attempted to elevate hind limbs so that their stifle joints were out of the water to decrease resistance during locomotion, which would have simultaneously increased tarsal joint flexion.

Results of the present study indicated that walking in various depths of water affected the amount of flexion and extension of each evaluated joint differently, including joints in the same limb; thus, the highest ROM was detected at different water depths for each evaluated joint. Additionally, the greatest flexion and extension of a joint (eg, fetlock joints) were not always detected at the same water depth. These findings suggested that clinicians and physical therapists should be aware of the effects of water depth on motion of joints of horses and should consider such effects when designing a rehabilitation program, especially if the goal of the rehabilitation exercise is to increase flexion or extension of particular joints or limbs. For instance, walking in a depth of water at the level of the tarsal joints may be indicated for a horse with reduced ROM of a carpal joint. Walking in a higher depth of water (ie, stifle joint water depth) may be indicated for a horse in which an increase in tarsal joint flexion and extension is desired. For horses with decreased ROM of fetlock joints, alternating exercise in each of 2 water depths (tarsal and fetlock joint water depths) may be indicated because walking in a depth of water at the level of the tarsal joints would increase fetlock joint flexion, and walking in a depth of water at the level of the fetlock joints would increase fetlock joint extension. These recommendations were determined on the basis of results of the present study. However, most horses in the study were Quarter Horses, and although the Thoroughbred included in the study had height, weight, and movement on the treadmill that were similar to those other horses, horses of other breeds may have different amounts of joint flexion and extension in various depths of water. Additionally, increases in activity of the various muscles involved in protraction and retraction of limbs should be considered when choosing a water depth for exercise (especially during the early rehabilitation period), to avoid fatigue or injury of muscles in horses that are not trained for exercise in water.

In another recent study,[27] horses walking on an underwater treadmill in water at the level of the carpal joints and the ulna had a lower stride frequency and a higher stride length of forelimbs, compared with those for horses walking in shallower water depths. Similarly, results of the present study indicated that the percentage duration of stance and swing phases of the stride of horses were affected by water depth; the percentage duration of the stance phase of the stride decreased, and the percentage duration of the swing phase increased with increasing water depth. Results of another study[31] indicate that horses trotting with tactile stimulators or weights attached to hind limb pasterns have an increased duration of the swing phase of the stride and an increased amount of flexion of stifle, tarsal, and fetlock joints.[31] Results of the present study indicated that similar effects were caused by exercise of horses on an underwater treadmill; such effects may have been attributable to water resistance or buoyancy. At the water depths evaluated in this study, water resistance was expected to increase with increasing water depth because water resistance is directly proportional to the amount of a limb submerged in water. In another study,[40] the effect of buoyancy on horses in a flotation tank filled with saline solution was evaluated; results of that study indicated horses had a 10% reduction in body weight when the fluid depth was at the level of the olecranon and horses had a 75% reduction in body weight when fluid depth was at the level of the tuber coxae. The effect of shallower depths of fluid on buoyancy of horses has not been determined, to the authors' knowledge, but results of another study[11] indicate the vertical ground reaction force of dogs only decreases by 9% after immersion in water to the level of the tarsal joints and decreases by 15% after immersion in water to the level of the stifle joints. Therefore, the effects of buoyancy on horses at the water depths evaluated in the present study were likely minimal.

Results of other studies indicate underwater treadmills are beneficial for rehabilitation of humans and other animals with orthopedic problems. For instance, exercise in water decreases joint effusion and pain in humans after orthopedic surgery.[1,2] Results of a recent study[41] indicate humans who undergo aquatic exercise after total knee arthroplasty have reduced joint pain and stiffness and improved joint function up to 6 months after discharge from the hospital. Aquatic exercise after surgery for treatment of cranial cruciate ligament rupture results in greater ROM of stifle and tarsal joints of dogs, compared with walking on land.[24] Similarly, dogs that undergo tibial plateau leveling osteotomy have improved limb function when early intensive postoperative physical therapy includes passive ROM exercises and training on an underwater treadmill.[25] To the authors' knowledge, similar studies have not been conducted for horses; therefore, the effects of underwater treadmill exercise in a rehabilitation program for horses are unknown. However, results of the present study indicated exercise on an underwater treadmill may be beneficial for horses with orthopedic problems because the ROM of joints of the distal aspects of limbs was found to be increased during such exercise.

The present study had several limitations attributable to the facilities in which the study was conducted; results may have been affected by these factors. These factors included the use of a 2-D imaging system, determination of data for left limbs only, placement of the video camera at an angle, and refraction of light in water. Therefore, the data may not have been precise, but the authors attempted to reduce the effects of these factors on the data so that results would be representative of characteristics of the motion of the distal aspects of limbs of horses. For humans[42] and small animals,[24] underwater kinematic analyses have been performed with 3-D data collection systems, but this was not possible for horses in the present study because of the physical characteristics of currently available underwater treadmills for horses. A 2-D data collection system was used in this study for kinematic analysis because videos could only be recorded through windows on the left side of the underwater treadmill. However, the size of the windows (90 × 70 cm) may have helped minimize the amount of error in the data because each stride was visible within that small area. Conversely, when performing 2-D stride analysis for horses walking over ground, data are typically determined for horses walking over a long distance, which may cause greater data error. By use of a 2-D data collection system in this study, only motion in a sagittal plane (the primary plane of limb movement) was analyzed. Horses walking in water may have more limb movement in nonsagittal planes versus horses walking on ground; data may have been affected by movement of limbs in nonsagittal planes. Only left forelimbs and hind limbs of horses could be evaluated in this study because the underwater treadmill did not have transparent windows on the right side. Despite this, results for left limbs may be applicable to right limbs because the walk is a symmetric gait and nonlame horses move their limbs symmetrically.[43] Another limitation that we could not eliminate because of characteristics of the underwater treadmill facility was the video camera angle (30° downward), which was necessary so that the motion of the most distal limb marker could be tracked. In addition, refraction of light in water likely affected the data. These factors likely reduced the sensitivity of our measurements. However, we attempted to minimize the effects of these factors; the same person placed markers on all of the horses, filled the underwater treadmill with water during all sessions, set up the video camera for each horse during each recording session, and manually checked selection of centers of markers in every video frame. In addition, 5 strides for each horse at each water depth were analyzed; this was intended to minimize variability attributable to the data collection system. We attempted to correct data for the camera position and refraction of light by water via analysis with a fixed angle (90°) in the underwater treadmill at all evaluated water depths and limb flexion and extension locations. Error corrections performed via this method should have further minimized variability in data; however, data were not corrected for error attributable to motion of the treadmill, water turbulence, or movement of limbs. On the basis of results of these analyses, we determined the error attributable to the equipment and refraction of light by water was < 3° for any evaluated joint and water depth, and we believe that the corrected results were representative of the motion of the distal aspects of limbs of the horses. In addition, the mean and SD values of the data determined in the present study were similar to those determined in other studies[44,45] in which limb kinematics of nonlame horses were evaluated during walking on ground.

Results of the present study indicated that an underwater treadmill may be useful for rehabilitation of horses because such exercise increased the overall ROM of joints of the distal aspects of limbs. Water depth affected the amount of flexion and extension of various joints differently. This information may be useful for clinicians or physical therapists trying to increase the overall ROM or amount of flexion or extension of limbs or joints of horses during rehabilitation exercise.

a. Equine Aquapacer, Ferno Veterinary Systems Inc, Wilmington, Ohio.
b. Lloyd Laboratories, Shenandoah, Iowa.
c. IDS Imaging Development Systems GmbH, Obersulm, Germany.
d. DMAS Equine Gait Trax, Motion Imaging Corp, Simi Valley, Calif.
e. SAS/STAT, version 9.2, SAS Institute Inc, Cary, NC.
f. Jackson AM, Millis DL, Stevens M, et al. Joint kinematics during underwater treadmill activity (abstr), in *Proceedings*. 2nd Int Symp Anim Phys Ther Rehabil Vet Med 2002;191–192.

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