Effect of underwater treadmill exercise on postural sway in horses with experimentally induced carpal joint osteoarthritis

Melissa R. King, DVM, PhD; Kevin K. Haussler, DVM, DC, PhD; Christopher E. Kawcak, DVM, PhD; C. Wayne McIlwraith, BVSc, PhD, DSc; Raoul F. Reiser II, PhD

Objective—To evaluate the effect of underwater treadmill exercise on static postural sway in horses with experimentally induced carpal joint osteoarthritis under various stance conditions.

Animals—16 horses.

Procedures—On day 0, osteoarthritis was induced arthroscopically in 1 randomly selected middle carpal joint of each horse. Beginning on day 15, horses were assigned to either underwater or overground (without water) treadmill exercise at the same speed, frequency, and duration. Two serial force platforms were used to collect postural sway data from each horse on study days –7, 14, 42, and 70. Horses were made to stand stationary on the force platforms under 3 stance conditions: normal square stance, base-narrow placement of the thoracic limbs, and removal of visual cues (blindfolded) during a normal square stance. The mean of 3 consecutive, 10-second trials in each condition was calculated and used for analysis.

Results—Displacement of the center of pressure differed significantly depending on the stance condition. Among horses exercised on the underwater treadmill, postural stability in both the base-narrow and blindfolded stance conditions improved, compared with findings for horses exercised on the overground treadmill. Horses exercised on the overground treadmill were only successful at maintaining a stable center of pressure during the normal square stance position.

Conclusions and Clinical Relevance—Variations in stance position had profound effects on the mechanics of standing balance in horses with experimentally induced carpal joint osteoarthritis. Underwater treadmill exercise significantly improved the horses’ postural stability, which is fundamental in providing evidence-based support for equine aquatic exercise. (Am J Vet Res 2013;74:971–982)

Postural stability is achieved through precise sensory or neural integration of proprioceptive, vestibular, and visual information.1 Effective postural control also relies on motor components of the musculoskeletal system to maintain balance, which include joint stability and neuromuscular control.2 Muscles are responsible not only for inducing joint motion, but also for stabilizing joints during limb loading and the maintenance of stance,3 thereby providing crucial contributions to balance control. Diminished sensory function and altered sensorimotor processing from articular structures substantially compromise the ability to maintain postural stability.4 Joint injury causes damaged and altered articular tissues, which ultimately impairs both the sensory and motor components required for postural stability.4 Therefore, slowing or preventing the progression of osteoarthritis is of particular interest because it affects the integrity of articular cartilage, exacerbates synovial membrane inflammation, and induces joint capsule fibrosis and periarticular muscle weakness.5,6 These disease processes directly alter the neurophysiologic properties of joint mechanoreceptors that aid in the control of tonic muscular activity responsible for joint stabilization during quiet standing.4

Joint mechanoreceptors provide continuous sensory input to the CNS regarding mechanical conditions in and around articulations. Joint mechanoreceptors are responsible for signaling joint position and movement, aid in controlling both the timing and direction of joint movement, contribute to the initiation of reflexive muscular responses that maintain joint stability, and have a primary role in joint nociception.6 Mechanoreceptors function as both proprioceptors and modifiers of
muscle activity, thereby monitoring joint stability and protecting articular structures from abnormal or excessive loading. Under normal circumstances, stretching of the joint capsule and surrounding ligaments causes increased firing of the joint mechanoreceptors; the mechanoreceptors synapse onto gamma motor neurons within the ventral horn of the spinal cord and induce fine adjustments in muscle tension that influence joint stability and balance. Musculoskeletal pain reduces reflex mechanisms mediated by joint mechanoreceptors, and an injured joint is protected from further damage either by inhibition of muscles or the stimulation of muscle guarding. Persistent joint pain and inflammation cause afferent excitatory stimulation of 1b interneurons within the ventral horn of the spinal cord, which induces inhibition of the muscles that act across the affected joint. Altered afferent articular information also decreases gamma motor neuron activation, which in turn alters muscle spindle sensitivity and ultimately impairs proprioception. Several studies in humans have revealed inhibitory muscle responses as a result of joint effusion, pain, and osteoarthritis. Increased knowledge of the neural and patterned muscle responses to joint effusion and osteoarthritis provides a deeper understanding of compensatory mechanisms involved in the maintenance of postural control and the prevention of additional musculoskeletal injuries.

Finely tuned adjustments in muscle tension are required to maintain positioning of the body’s COM during an upright stance. While humans stand quietly on a force platform, these slight adjustments in muscle tension induce movement that can be objectively measured as movement of the COM in both mediolateral and craniocaudal directions. Force platforms are used to record changes in the COP, which is defined as the point of application of the ground reaction forces under the feet. The trajectory (ie, amplitude and pattern) of the COP provides insights into the process of balance control because changes in the COP are directly related to motion of an individual’s COM. Postural sway is defined from measures of COP movement in craniocaudal or mediolateral directions. Excessive postural sway in a mediolateral direction is often used to predict whether humans are at risk for falling. Individuals with proprioceptive deficits will have a large COP area because of altered signaling pathways that diminish the ability of neuromuscular responses to maintain postural stabilization during stance. In humans, osteoarthritis can induce subclinical musculoskeletal dysfunction, which can be quantitatively measured by means of postural sway analysis during quiet standing. Humans with osteoarthritis of the knee and hip joints have significantly greater postural sway disturbances, compared with findings for age-matched healthy individuals, which indicates that osteoarthritis negatively affects balance and postural stability. In addition, electromyography of the quadriceps muscle group in humans with knee joint osteoarthritis often reveals a decrease in muscle strength and delayed activation. Abnormal timing or amplitudes of quadriceps muscle group activation can cause balance deficits and a reduction in the ability to maintain, achieve, or restore postural stability. Increased COP displacement in either craniocaudal or mediolateral directions helps to identify altered neuromuscular response mechanisms responsible for maintaining stance in humans during postural sway analysis.

Postural sway analysis in humans is often assessed in both a double- and single-leg stance position and with subjects tested with their eyes open and closed. A single-leg stance position requires substantially more motor control and strength than does a double-leg stance position. Assessments performed with a subject’s eyes closed are often undertaken to assess the contribution of visual pathways to postural stability. Changes in stance position and the removal of visual cues provide valuable information regarding the severity of balance deficits present in humans with osteoarthritis and are effective in assessing the degree of improvement in postural sway variables following exercise interventions.

The subjective assessment of a horse’s response to balance-related manipulative tests (ie, when horses are placed in a crossed-limb stance or are blindfolded) are routinely incorporated into clinical neurologic examinations. However, the relationship between changes in stance conditions and the associated balance deficits in horses remains inconclusive. Recent research has demonstrated that force platform analysis provides a reliable assessment of postural stability in horses. The quantification of balance control by means of postural sway analysis can be a valuable tool for the diagnosis of subclinical neuromuscular and musculoskeletal conditions and in the monitoring of the response to rehabilitation. Horses with abnormal sensory or afferent signaling attributable to joint pain, inflammation, or altered muscle activation are likely to have impaired motor control. Therefore, identifying alterations in static postural stability and the effects of impaired motor control on balance required during dynamic locomotor tasks (eg, half pass, leg yield, piaffe, and pirouette) will aid in the development of targeted diagnostic and treatment strategies.

Physical rehabilitation has become an effective treatment option for primary musculoskeletal injuries and for reducing or limiting harmful compensatory gait abnormalities in humans. Rehabilitation programs that address osteoarthritis and musculoskeletal injuries often incorporate some form of aquatic exercise. Exercising in water provides an effective medium for increasing joint mobility, increasing muscle activation, promoting normal motor patterns, and reducing the incidence of secondary musculoskeletal injuries. Humans with osteoarthritis of the joints of the lower extremities have a significant reduction in the amplitudes of postural sway following aquatic exercise. The improved muscle strength and function associated with aquatic exercise significantly improve proprioception and motor control and reduce the abnormal postural sway characteristics typically reported in osteoarthritic adults. The application of water exercise may enhance motor learning through multisensory impulses, thereby improving posture and stability.

Underwater treadmill exercise is widely used in the rehabilitation of horses with osteoarthritis and other musculoskeletal injuries. To our knowledge, no studies...
to date have specifically assessed the efficacy of underwater treadmill exercise with regard to horses. Therefore, the overall goal of the study reported here was to evaluate the effects of underwater treadmill exercise on static postural sway in horses with experimentally induced carpal joint osteoarthritis under various stance conditions. Characterization of altered postural stability associated with joint pain and osteoarthritis is critical for developing targeted, clinically relevant diagnostic and treatment strategies to minimize the progression of joint degeneration and compensatory changes that may lead to additional musculoskeletal injuries. Therefore, the study was designed to assess static postural sway of the horses under conditions of normal square stance, base-narrow stance (ie, base-narrow placement of the thoracic limbs), and normal square stance with removal of visual cues (ie, blindfolded) and to evaluate the effects of underwater treadmill exercise on static postural sway. Our hypotheses were that the base-narrow and blindfolded stance conditions would diminish postural stability and that horses with experimentally induced carpal joint osteoarthritis exposed to underwater treadmill exercise would have improved postural sway characteristics, compared with horses with experimentally induced carpal joint osteoarthritis that underwent overground treadmill exercise, which simulates controlled hand walking.

Materials and Methods

Project design—The horses of this study were not permanently disabled by experimental induction of carpal joint osteoarthritis, considering that they were euthanized at the conclusion of the study as part of a larger project investigating the gross morphological, histologic, and biochemical outcomes associated with the progression of osteoarthritis and quantifying the disease-modifying effects of underwater treadmill exercise. Nonlame horses were not used in the study because the displacement in the COP measurements used to determine the effects of underwater treadmill exercise was not expected to be of sufficient magnitude to identify any changes in a clinically normal horse population.

Horses—Sixteen skeletally mature horses ranging in age from 2 to 4 years (mean ± SD body weight, 385 ± 40 kg; mean height measured from the ground to the most dorsal aspect of the shoulders [ie, withers], 1.46 ± 0.04 m) were included in the study. Prior to inclusion in the study, all horses underwent body condition assessment, a lameness examination, range of motion (flexion) testing of the carpal joints, evaluation for the presence of middle carpal joint effusion, and radiography of the carpal joints; only horses without abnormal findings were permitted into the study. A minimum 14-day acclimatization period was provided prior to baseline data collection to introduce new environmental factors and to train the horses to safely enter and use the overground and underwater treadmills. The Colorado State University Institutional Animal Care and Use Committee approved the study protocol.

Experimental induction of osteoarthritis—Each horse was anesthetized and routinely prepared for surgery. Each horse underwent bilateral arthroscopic surgery of the middle carpal joints (day 0) to ensure that there were no preexisting articular lesions. During this procedure, an osteochondral fragment was created in a randomly selected middle carpal joint of each horse. An 8-mm-wide fragment was generated with an 8-mm curved osteotome directed perpendicular to the articular cartilage surface of the radial carpal bone at the level of the medial synovial plica. The dorsal surface of the osteochondral fragment was allowed to remain adhered to the joint capsule proximally. A motorized burr was used to debride the exposed subchondral bone between the fragment and the parent bone to create a 15-mm-wide defect bed. The debris was not actively lavaged from the joint. Diagnostic arthroscopy was performed on the contralateral middle carpal joint to ensure absence of any joint disease. The arthroscopic portals were closed with 2-0 nylon suture in a simple interrupted pattern, and cyanoacrylate glue was applied to the skin incision. The thoracic limbs were bandaged, and the horse was allowed to recover from anesthesia and surgery. Each horse received a single dose of ceftiofur (4.0 mg/kg, IM) just prior to surgery and 2 g of phenylbutazone orally once a day for 5 days after surgery. Bandages were changed every 3 to 5 days and maintained until suture removal was performed 10 days after surgery. Animal-care personnel assessed horses daily for apparent comfort, movement, and respiratory character throughout the study. At the end of the study, all horses were euthanized by IV administration of pentobarbital sodium.

Exercise—Horses were individually housed in 3.7 × 3.7-m stalls. Beginning on day 15, all horses were exercised on a high-speed overground treadmill 5 days each week until the end of the study to promote the development of osteoarthritis. Each day, the horses were trotted at 4.4 m/s for 2 minutes, galloped at 8.8 m/s for 2 minutes, and trotted again at 4.4 m/s as part of a standard exercise protocol used to aid in the induction and progression of carpal joint osteoarthritis.

Treatment groups—One week after surgery (day 7), the horses were ranked by lameness scores and randomly assigned to 1 of 2 groups, with 8 horses in each group. The aquatic exercise group was exposed to underwater treadmill exercise starting on day 15. The underwater treadmill protocol consisted of exercise at a brisk walk (2.1 m/s) for 5 minutes, once a day, for 5 days. The water level in the underwater treadmill was maintained at the point of the shoulder for the duration of the study, which reduced weight bearing by approximately 60%. At weekly intervals, the duration of underwater treadmill exercise was increased by 5 minutes, until a maximum of 20 min/session was reached. Horses then continued to be exercised for 20 minutes once a day, 5 days a week, for the remainder of the 10-week study (ie, 8 weeks of exercise). The control group was exercised on an overground treadmill (without water) in a manner similar to that of the underwater treadmill protocol for the intervention group (ie, same speed, frequency, and duration of exercise), also starting at day 15. The overground treadmill exercise planned for the control group was designed to simulate conventional
hand walking and light exercise used for rehabilitation after arthroscopic surgery.

**Kinetic data collection**—Displacement of the COM of each horse’s body was determined from COP measurements recorded with 2 strain-gauge–based force platforms (60 X 90 cm) mounted in series in a concrete base at the center of a 25-m runway. The COP accuracy for each force platform was ± 2 mm, and the static resolution for the system was ± 1 N. Postural sway data were collected from each horse at 4 time points during the study: prior to induction of the osteochondral fragment (day −7), after induction of the osteochondral fragment and 1 day prior to initiating treadmill exercise (day 14), 4 weeks after initiating treadmill exercise (day 42), and at study conclusion (day 70).

**Stance conditions**—Postural control was assessed in 3 stance conditions: normal square stance with vertical placement and even weight distribution on all 4 limbs, base-narrow placement of the thoracic limbs, and normal square stance with removal of visual cues (ie, blindfolding). Each horse was positioned with their thoracic limb hooves squarely placed on a force platform and their pelvic limb hooves placed squarely on the second force platform. The horse handler was instructed to stand in front of the horse and to hold the lead shank loosely with no direct contact while an assistant stood on either side of the horse near the pelvic limbs to encourage a static stance. The placement of each hoof was marked with chalk on the surface of the force platform, and the distance between each outlined hoof and the lateral edges of the force platform was recorded to provide consistent hoof placement across all trials (ie, the distance between the lateral aspect of the hoof wall and the lateral edge of the force platform were measured). Each horse was initially positioned on the force platforms in a normal stance position with the head and neck maintained in a relaxed, neutral position. For the second stance condition, the thoracic limbs were placed with the medial aspect of each hoof in contact with each other in a base-narrow stance position and the toes at equal distance from the cranial aspect of the force platform. The third stance condition involved returning the thoracic limbs to a normal square stance position and placement of a blinder hood over the horse’s head that completely blocked vision in both eyes (Figure 1). For each stance condition, each horse was required to stand quietly for 3 consecutive, 10-second trials. The mean of the 3 trial results in each condition was calculated and used for analysis.

**Kinematic data collection**—Kinematic data were used to determine the 2-D position of hoof placement on the force platforms. For each horse, cyanoacrylate glue was used to attach 2.5-cm, round, reflective markers to the mid-dorsum of each hoof (3 cm distal to the coronary band) and on the midline of the forehead between the supraorbital foramina. Trials with head and neck displacements > 20 cm in any direction were excluded because movements of the head and neck are known to cause substantial changes in COP measurements. Kinematic data were collected at 200 Hz with a motion analysis system and 8 high-speed infrared cameras distributed equally around the periphery of the force platforms. The capture volume over the region of the force platforms was calibrated with a customized calibration frame and wand with an accuracy of 0.71 mm.

**Data processing**—The COP data were collected at a sampling rate of 3,000 Hz and low-pass filtered with a fourth-order, recursive Butterworth filter at 15 Hz to remove noise. The COPs in both the craniocaudal and mediolateral directions were determined initially from each force platform and later combined to calculate a net COP in craniocaudal (y) and mediolateral (x) directions from the following equation:

$$\text{Net COP}_i = (\text{COP}_i \text{ plate 1} \times \left[ \frac{F_z \text{ plate 1}}{F_z \text{ plate 1} + F_z \text{ plate 2}} \right]) + \left( \text{COP}_i \text{ plate 2} \times \left[ \frac{F_z \text{ plate 2}}{F_z \text{ plate 2} + F_z \text{ plate 1}} \right] \right)$$

where COP, is the COP recorded in either the craniocaudal (i = y) or mediolateral (i = x) direction measured independently from force platform 1 or 2, and $F_z$ plate 1 and $F_z$ plate 2 are vertical ground reaction forces recorded from the respective force platforms. Stabilograms were created to illustrate the movement of the net COP in craniocaudal (y) and mediolateral (x) directions for the 3 stance conditions.

**Postural sway variables**—Postural sway variables were calculated from the net COP for each stance condition. Craniocaudal sway (mm) was calculated as the range of COP displacements in a craniocaudal direction (COPy) relative to the horse, where positive values indicate cranial movements. Mediolateral sway (mm) was calculated as the range of COP displacements in a mediolateral direction (COPx) relative to the horse. The kinematic and electromyography data were collected as part of a larger study.
a mediolateral direction (COPy), where positive values indicate movements toward the right. The COP area (mm²) was calculated as the extreme bounds of the COP movement in both craniocaudal and mediolateral directions. The COP velocity (mm/s) is defined as the direction and amplitude of COM displacement immediately following time instant. The average velocity was calculated by summing the resultant distance between 2 consecutive COP data points divided by time. The COP radius (mm) was calculated as the mean displacement of each COP data point (xi, yi) relative to the geometric center (ie, mean location of the COP = x0, y0) of each stance condition.

Kinematic stance position variables—Because the hooves did not move during each trial, the 3-D transformed orthogonal coordinates of the reflective markers placed on the dorsal aspect of the hoof wall were used to determine the hoof positions at time 0. Cranio-caudal length (m) was calculated as the distance between the midpoint of the 2 thoracic limb hoof markers and the midpoint of the 2 pelvic limb hoof markers. Mediolateral width (m) was calculated as the distance between the calculated midpoint of the right thoracic and left pelvic limb hoof markers and the calculated midpoint of the left thoracic and right pelvic limb hoof markers. Base of support (m²) was calculated as the total area contained within the 4 hoof marker locations. Head height (m) was calculated as the mean vertical distance between the reflective markers located on the forehead and the left thoracic limb hoof.

Normalization procedure—Prior to statistical analysis, the postural sway variables (Table 1) were normalized to the corresponding kinematic measurements and reported as a normalized percentage value (eg, postural sway variable divided by stance position variable times 100%). Normalization was used to remove the dependence of the postural sway variables on each individual horse's morphometric features. The cranio-caudal sway was normalized to the cranio-caudal length (Table 2). Similarly, mediolateral sway was normalized to the mediolateral width, COP area was normalized to the base of support area, and head height was normalized to the height at the withers for each horse.

Assessment of thoracic limb loading patterns—The combined COPs for the thoracic limbs in both the cranio-caudal and mediolateral directions were measured from a single force platform (plate 2). The direction of COP movement relative to thoracic limb hoof placement was determined with customized programming. The direction of COP movement toward or away from the limb with the surgically created osteochondral fragment in the carpal joint was determined for each of the postural sway variables at the 4 time points during all stance conditions.
Clinical outcomes—For each horse, clinical examinations of both thoracic limbs were performed weekly from day –7 (baseline; before surgery) throughout the study period. Lameness was graded by an experienced equine orthopedic surgeon, who was unaware of the treatment group assignments, using a standardized American Association of Equine Practitioners lameness scale wherein 0 represented normal gait and 5 represented severe lameness (with the horse trotting on hard ground).

Data analysis—The COP data measured sequentially at different time points over the course of the study were evaluated with a commercially available statistical software program with an ANOVA or ANCOVA framework depending on the presence or absence of a covariate, respectively. An ANOVA was also used to determine the influence of stance positions on the dependent postural sway variables. The ANOVA design involved assessing the COP variables obtained at days –7 and 14 (pretreatment analysis) to demonstrate that no treatment group effect was detectable prior to the initiation of underwater treadmill exercise. The ANCOVA was designed to assess the posttreatment postural sway variables (ie, data obtained on days 42 and 70), with day 14 as a covariate to adjust for any influences that existed at that time point. The ANOVA tables were used to determine significant main effects and interactions between main effect variables. When individual comparisons were made, least squares means were used. Values were reported as mean ± SEM, and values of P < 0.05 were considered significant.

### Results

**Craniocaudal sway**—Craniocaudal sway differed significantly (P = 0.04) depending on the stance position; when blindfolded horses had the largest amplitudes of craniocaudal sway, compared with the base-narrow and normal square stance positions (Table 3). Pretreatment analysis (data from days –7 and 14) revealed that craniocaudal sway did not differ significantly depending on whether the horse was in the aquatic exercise or control group (ie, no main effect of treatment group). However, posttreatment analysis (data from days 42 and 70) revealed that craniocaudal sway was significantly (P < 0.001) influenced by the presence or absence of aquatic exercise. Horses exercised on the underwater treadmill had significantly decreased craniocaudal sway, compared with that of the control group (Table 4). When specific individual comparisons were conducted, craniocaudal sway in the blindfolded normal square stance position was significantly decreased at days 42 (P = 0.004) and 70 (P = 0.03) in the aquatic exercise group, compared with findings in the control groups (Figure 2). Similarly, horses exercised on the underwater treadmill had significantly decreased craniocaudal sway when standing in a base-narrow stance position on both days 42 (mean ± SEM, 1.1 ± 0.2%; P = 0.03) and 70 (1.0 ± 0.2%; P = 0.009), compared with the control horses (1.7 ± 0.2%).

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**Table 2**—Mean ± SEM normalized postural sway variables obtained from the 2 groups of horses in Table 1 at 28 and 56 days after commencement of treadmill exercise (ie, days 42 and 70 after surgical creation of an osteochondral fragment in 1 randomly selected carpal joint), controlling for the effect of stance position and study day.

**Table 3**—Mean ± SEM normalized postural sway variables obtained from the horses in Table 1 when they were in a normal square stance position, a base-narrow stance position, and a blindfolded normal square stance position, controlling for the effects of time and treatment group.

**Table 4**—Mean ± SEM postural sway variables obtained from the 2 groups of horses in Table 1 at 28 and 56 days after commencement of underwater treadmill exercise (UWT; n = 8) or overground treadmill exercise (control; 8).

### Table 2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day –7</th>
<th>Day 14</th>
<th>Day 42</th>
<th>Day 70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craniocaudal sway (%)</td>
<td>1.6 ± 0.2</td>
<td>1.5 ± 0.2</td>
<td>1.6 ± 0.2</td>
<td>1.6 ± 0.2</td>
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<tr>
<td>Mediallateral sway (%)</td>
<td>1.4 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>1.2 ± 0.2</td>
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<tr>
<td>COP area (%)</td>
<td>4.9 ± 0.9</td>
<td>4.3 ± 0.9</td>
<td>3.8 ± 0.9</td>
<td>3.7 ± 0.9</td>
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<td>COP velocity (mm/s)</td>
<td>0.9 ± 0.9</td>
<td>0.8 ± 0.9</td>
<td>0.6 ± 0.9</td>
<td>0.6 ± 0.9</td>
</tr>
<tr>
<td>COP radius (mm)</td>
<td>77.6 ± 28.4</td>
<td>63.6 ± 28.4</td>
<td>46.7 ± 28.4</td>
<td>52.7 ± 28.4</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Stance position</th>
<th>Normal</th>
<th>Base-narrow</th>
<th>Blindfolded</th>
</tr>
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<tbody>
<tr>
<td>Craniocaudal sway (%)</td>
<td>1.3 ± 0.1</td>
<td>1.4 ± 0.1</td>
<td>1.6 ± 0.1</td>
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<tr>
<td>Mediallateral sway (%)</td>
<td>4.8 ± 0.5</td>
<td>6.5 ± 0.5</td>
<td>6.0 ± 0.5</td>
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<tr>
<td>COP area (%)</td>
<td>69.0 ± 17.7</td>
<td>112.0 ± 17.7</td>
<td>126.0 ± 17.7</td>
</tr>
<tr>
<td>COP velocity (mm/s)</td>
<td>13.9 ± 1.1</td>
<td>14.8 ± 1.1</td>
<td>16.1 ± 1.1</td>
</tr>
<tr>
<td>COP radius (mm)</td>
<td>4.6 ± 0.3</td>
<td>4.5 ± 0.2</td>
<td>4.7 ± 0.3</td>
</tr>
</tbody>
</table>

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**Table 4**

<table>
<thead>
<tr>
<th>COP variable</th>
<th>Control</th>
<th>UWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Craniocaudal sway (%)</td>
<td>1.7 ± 0.1</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>Mediallateral sway (%)</td>
<td>6.6 ± 0.3</td>
<td>4.4 ± 0.3</td>
</tr>
<tr>
<td>COP area (%)</td>
<td>132.5 ± 11.0</td>
<td>56.0 ± 11.0</td>
</tr>
<tr>
<td>COP velocity (mm/s)</td>
<td>15.1 ± 0.8</td>
<td>12.5 ± 0.8</td>
</tr>
<tr>
<td>COP radius (mm)</td>
<td>5.5 ± 0.2</td>
<td>3.6 ± 0.2</td>
</tr>
</tbody>
</table>

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**Table 3**—Mean ± SEM normalized postural sway variables obtained from all 16 horses in Table 1 when they were in a normal square stance position, a base-narrow stance position, and a blindfolded normal square stance position, controlling for the effects of time and treatment group.

**Table 4**—Mean ± SEM postural sway variables obtained from the 2 groups of horses in Table 1 at 28 and 56 days after commencement of treadmill exercise (ie, days 42 and 70 after surgical creation of an osteochondral fragment in 1 randomly selected carpal joint), controlling for the effect of stance position and study day.

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**Table 1** for remainder of key.

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Within a row, different superscript letters indicate significant (P < 0.05) differences between the stance positions. See Tables 1 and 2 for remainder of key.
Mediolateral sway—Mediolateral sway differed significantly ($P < 0.01$) depending on the stance position. Significantly increased amplitudes of mediolateral sway were evident in the base-narrow and blindfolded normal square stance positions, compared with that in the normal square stance position (Table 3). No significant differences were detected in mediolateral sway between the base-narrow and blindfolded normal square stance positions. Pretreatment analysis (data from days –7 and 14) revealed that mediolateral sway did not differ significantly between the aquatic exercise and control groups. However, posttreatment analysis (data from days 42 and 70) revealed that horses undergoing underwater treadmill exercise had significantly ($P < 0.001$) reduced mediolateral sway, compared with that of control horses (Table 4). Results of least squares mean comparisons indicated that mediolateral sway on posttreatment days 42 and 70 was significantly different depending on stance position and the presence or absence of aquatic exercise. Horses exercised on the underwater treadmill had significantly ($P = 0.02$) decreased mediolateral sway when blindfolded in the normal square stance position on day 42 ($4.8 \pm 0.7\%$), compared with that of the horses exercised on the overground treadmill ($7.1 \pm 0.7\%$). Similarly, the aquatic exercise group had significantly ($P = 0.01$) decreased mediolateral sway when standing in a base-narrow stance position on day 42 ($4.8 \pm 0.7\%$), compared with that of the control group ($8.2 \pm 0.7\%$). Lastly, horses undergoing aquatic exercise had significantly reduced mediolateral sway in the normal square stance position on both days 42 ($P = 0.01$) and 70 ($P = 0.04$), compared with findings for horses in the control group (Figure 3).

COP area—The removal of visual cues by blindfolding in a normal square stance position caused a significantly ($P = 0.02$) larger area of COP movement, compared with that in a nonblindfolded normal square stance position (Figure 4). Similarly, the base-narrow stance position had a significantly larger COP area, compared with that in a normal square stance position. As expected, the pretreatment analysis (data from days –7 and 14) revealed that COP area did not differ

Figure 2—Mean ± SEM normalized amplitudes for craniocaudal COP movement during the blindfolded normal square stance position (ie, vertical placement and even weight distribution on all 4 limbs with blindfolding) in horses with a surgically created osteochondral fragment in 1 randomly selected carpal joint that subsequently underwent underwater treadmill exercise (UWT; $n = 8$) or overground treadmill exercise (control; 8) as determined on days 42 and 70 (osteochondral fragmentation was induced on day 0, and treadmill exercise commenced on day 15). Amplitudes for this variable are reported as a normalized percentage value (eg, postural sway variable divided by stance position variable times 100%). Values with different letters are significantly ($P < 0.05$) different between the treatment groups within and across the study days.

Figure 3—Mean ± SEM normalized amplitudes of the mediolateral COP movement during the normal square stance position (ie, vertical placement and even weight distribution on all 4 limbs) in horses with a surgically created osteochondral fragment in 1 randomly selected carpal joint that subsequently underwent underwater treadmill exercise (UWT; $n = 8$) or overground treadmill exercise (control; 8) as determined on days 42 and 70 (osteochondral fragmentation was induced on day 0 and treadmill exercise commenced on day 15). Amplitudes for this variable are reported as a normalized percentage value (eg, postural sway variable divided by stance position variable times 100%). Values with different letters are significantly ($P < 0.05$) different between the treatment groups within and across the study days.
significantly depending on whether the horse was undergoing underwater or overground treadmill exercise. In contrast, posttreatment analysis (data from days 42 and 70) revealed significantly ($P < 0.001$) smaller COP areas for horses exercised on the underwater treadmill, compared with horses exercised on the overground treadmill (Table 4).

COP velocity—Changing stance position alone was effective in influencing the COP velocity. A lack of visual stimulation (ie, blindfolding) in the normal square stance position caused a significantly ($P = 0.007$) greater velocity in the COM displacement, compared with that in a nonblindfolded normal square stance position (Table 3). The COP velocity was not significantly different between the blindfolded normal square and base-narrow stance position or between the base-narrow and normal square stance positions. Pretreatment analysis (data from days –7 and 14) revealed that COP velocity did not differ significantly depending on whether the horse was undergoing underwater or overground treadmill exercise. The presence or absence of aquatic exercise significantly ($P = 0.05$) influenced the COP velocity in the posttreatment analysis (data from days 42 and 70). Specifically, the aquatic exercise group maintained a slower COP velocity and thus better balance restraint, compared with findings for the control group (Table 4).

COP radius—Alterations in stance position did not significantly influence the COP radius (Table 3), and pretreatment analysis (data from days –7 and 14) revealed no significant difference between the aquatic exercise and control groups. However, the COP radius was significantly influenced by the presence or absence of aquatic exercise in the posttreatment analysis (data from days 42 and 70; Table 4). The horses undergoing underwater treadmill exercise had a significantly ($P < 0.001$) smaller COP radius than that of the horses undergoing overground treadmill exercise across all 3 stance positions.

Cranio-caudal length—the cranio-caudal length was significantly ($P = 0.006$) influenced by the 3 stance positions. Specifically, the normal square stance position had a significantly smaller cranio-caudal length (1.06 ± 0.01 m), compared with lengths for both the blindfolded normal square stance position (1.07 ± 0.01 m; $P = 0.02$) and base-narrow stance position (1.08 ± 0.01 m; $P = 0.002$). No significant differences were detected.
between the craniocaudal lengths for the base-narrow and blindfolded normal square stance positions. Study day and the presence or absence of aquatic exercise did not significantly influence craniocaudal length.

**Mediolateral width**—The base-narrow stance position had a significantly (P < 0.001) smaller mediolateral width (0.210 ± 0.005 m), compared with widths for both the blindfolded (0.250 ± 0.005 m) and the normal square stance positions (0.250 ± 0.005 m). No significant differences were detected between the normal and blindfolded mediolateral width. Study day and the presence or absence of aquatic exercise did not significantly influence mediolateral width.

**Head height**—The height of the head was significantly (P < 0.001) lower in the base-narrow stance position (88.0 ± 2.0%), compared with the height of the head in the blindfolded normal square stance position (92.0 ± 2.0%). Head height did not significantly differ between the normal square (90.0 ± 2.0%) and base-narrow stance positions; likewise, head height did not differ between the blindfolded and nonblindfolded normal square stance positions. Height of the head did not significantly change among study days for each stance position, and a significant difference was not detected between the 2 groups of horses.

**Clinical examinations**—Mild lameness (mean score, 1.81 ± 0.05) was evident in all limbs of horses in which an osteochondral fragment was surgically created. This mean lameness score differed significantly (P < 0.001) from the baseline value determined before osteoarthritis was induced (0.03 ± 0.09), and the difference persisted throughout the study period (Figure 5). The mean lameness score for the limbs with a surgically created osteochondral fragment in the carpal joint in horses that underwent aquatic exercise (2.5 ± 0.2) was significantly (P = 0.04) higher at day 21 (7 days after the initiation of aquatic exercise), compared with the score for the limbs with a surgically created osteochondral fragment in the carpal joint of horses in the control group (2.0 ± 0.2). However, the mean lameness scores for the limbs with a surgically created osteochondral fragment in the carpal joint in horses that underwent aquatic exercise at day 42 (1.4 ± 0.2) and day 49 (1.9 ± 0.2), which was 28 and 35 days after the initiation of aquatic exercise, were significantly (P = 0.04) lower, compared with the scores for the limbs with a surgically created osteochondral fragment in the carpal joint of horses in the control group (1.9 ± 0.2 and 2.4 ± 0.2, respectively). Lameness scores for the horses that underwent underwater treadmill exercise decreased beginning on day 28 and continued for the remainder of the study, although significant differences between the 2 groups were only evident on days 42 and 49. Overall, there was no significant difference in the subjective lameness scores with respect to treatment.

**Discussion**

In humans, evaluation of balance control through postural sway analysis is a reliable and valid approach to determining static stability under various conditions.\(^{10,21,23}\) Results of the present study indicated that underwater treadmill exercise significantly improves static balance control in horses with carpal joint osteoarthritis, which is pivotal to initiating evidence-based support for the use of aquatic exercise in the management of joint disease in this species. This study has also provided the first evidence that variations in stance positions have profound effects on the mechanics of standing balance in horses. Direct measurement of changes in the COP movements confirmed that a narrow stance width and removal of visual stimuli significantly decreased postural stability.

Balance control is a dynamic task in which sensorimotor systems must interact with the external environment to maintain stability.\(^{31}\) One of the most striking findings of the present study was that when the horses’ thoracic limbs were placed in a base-narrow stance position, there was a significant increase in mediolateral sway but no change in craniocaudal sway. This may be explained by the mechanical differences in joint structure and function that contribute to motion or stability within the 2 planes of movement. Under normal circumstances, mediolateral stability of thoracic limb articulations is provided by robust, periarticular collateral ligaments.\(^{25}\) However, joint motion within a sagittal plane is normally achieved by the flexion-extension of the highly mobile hinge joints within the thoracic and pelvic limbs.\(^{21}\) In humans with mediolateral specific instability, a wider stance width is often adopted to reduce the lateral COP displacement. The increase in stance width reduces the lateral rotation about the ankle joint, thereby decreasing angular motion and improving mediolateral stabilization.\(^{21}\) The ankle, knee, and hip joints move independently in the sagittal plane, allowing for increased control of the COP movement in a craniocaudal direction during postural...
sway analysis. However, lateral joint movement in the frontal plane cannot occur independently: a change in one joint angle leads to predictable angle changes in the other joints. In a feet-together stance position, people often have increased mediolateral COP displacement because of increased lateral rotation about the ankle joint, which leads to enhanced proprioceptive signaling and increased recruitment of the pelvis and hip musculature to change the position of the hip joint to improve balance control. Evidence of a similar neuromuscular adaption would be expected during postural sway analysis in horses. A base-narrow stance position may also alter the direction of the ground reaction force vectors, thereby changing the force distribution across the joint surfaces. In particular, by reducing the size and configuration of the base of support, the horizontal force vectors become more laterally directed, which leads to excessive joint loading and instability. The altered force vector orientation may cause a counterproductive secondary increase in muscle activation, which results in increased levels of tonic muscle activity and large fluctuations in the COP. The base-narrow stance data obtained in the present study suggested that hoof position is an important determinant of standing balance in horses and should be considered when altering hoof position through trimming and shoeing applications or when certain terrain characteristics force a horse to move or stand in a base-narrow stance position.

The visual system is a major contributor to balance control, providing both spatial and temporal information. The removal of visual cues requires an increased reliance on proprioceptive and vestibular sensory cues to maintain balance, which signal body movement relative to the foot and head. Reduced afferent information results in less precise balance control because the CNS has less information with which to accurately estimate and control the COM position and velocity. In the present study, the blindfolded normal square stance position resulted in larger and more rapid displacements of the COP, which indicates a high reliance of postural control on visual cues in horses. This finding is consistent with the well-documented phenomenon of impaired balance control in humans who are standing with their eyes closed. The loss of visual cues also causes an increase in muscle stiffness and alters postural sway, thereby impacting reflexive responses to alterations in COM movement. In human studies, the compensatory effects of vision under conditions of muscular fatigue have been identified. In those studies, the destabilizing effects of muscular fatigue on balance control were significantly compensated for when individuals stood with their eyes open versus eyes closed. In addition, elderly humans typically have progressive loss of their peripheral vision, which causes reduced regulation of COM movements, subsequently increasing the risk of falling. The present study’s findings have indicated that the removal of visual cues is an important determinant of standing balance control in horses and should strongly be considered when visual input is restricted for the purposes of various athletic activities (e.g., application of blinders). However, a limitation of the present study was that horses were only assessed in a completely blindfolded and static condition; future studies need to address various forms of partial to complete blockade of visual stimuli in both static and dynamic settings.

The present study has provided the evidence that underwater treadmill exercise improves static balance control in horses with carpal joint osteoarthritis. The increased resistance and buoyancy inherent in aquatic exercise minimize joint instability and weight-bearing stresses applied to limbs. Humans with osteoarthritis who are involved in aquatic treatment programs often have a significant reduction in pain, increase in muscle strength, and improvement in motor control. Aquatic exercise reduces postural sway in women with osteoarthritis of the lower extremities, as demonstrated in 2-legged stance tests with the eyes closed. The most notable differences in postural stability of the horses in the present study were associated with the blindfolded state, when affected horses were deprived of visual cues and had to rely on vestibular and somatosensory input to maintain balance. Underwater treadmill exercise improved balance control in both the base-narrow and blindfolded normal square stance positions, whereas the control group maintained balance only when placed in a normal square stance position. Underwater treadmill exercise may have increased the afferent excitation of the motor neuron pool for the muscles responsible for stabilizing the thoracic and pelvic limbs. Therefore, sensory receptors (e.g., muscle spindles, Golgi tendon organs, and joint mechanoreceptors), afferent transmission, and efferent motor control may have been positively affected through aquatic exercise, which resulted in improved postural control in those horses. Underwater treadmill exercise increases joint mobility, reduces signs of pain and inflammation associated with impact loading, promotes normal motor patterns, and increases proprioceptive acuity and postural control. Horses in the control group had a greater disturbance in postural stability, specifically when challenged with conditions requiring increased proprioceptive input and motor control for maintaining equilibrium. Increased variation in postural sway characteristics within the control group may be associated with increased stimulation of nociceptive pathways and altered afferent signaling from the joint mechanoreceptors as a result of joint pain and inflammation. Altered sensory feedback caused by synovial effusion and inflammation leads to altered muscle activity, which may ultimately impair a horse’s ability to make motor output adjustments efficiently during functional mobility and dynamic control of balance.

During dynamic gait analysis, the decreased lameness scores for the horses undergoing underwater treadmill exercise corresponded with an improvement in postural sway variables at similar time points. Although underwater treadmill exercise did not have a beneficial effect on lameness scores at all time points, the improvements in balance control under various stance positions in those horses that underwent underwater treadmill exercise may translate into improved functional locomotion. Humans that undertook a 12-week aquatic exercise program had improvements in static postural control and dynamic balance test results. Aquatic exercise affects both balance and strength, which translates into...
improved dynamic control on land. The enhanced af-
ferent input used to maintain the position of the base
of support in those horses exercised on the underwater
treadmill in the present study establishes a foundation
for precise dynamic neuromuscular control.
For the horses of the present study, surgical creation
of an osteochondral fragment in a carpal joint influenced
the magnitude of craniocaudal COP displacement in both
the base-narrow and blindfolded normal square stance
positions. Under both of these conditions, horses in the
control group were more likely to shift the craniocaudal
COP away from the limb with a surgically created osteo-
chondral fragment in the carpal joint, thereby unloading
the injured or painful joint. This shift in the COP may
be attributable to the creation of the osteochondral frag-
ment, which remains adhered to the joint capsule prox-
ially and may subsequently influence the sensitivity of
the joint capsule mechanoreceptors. Altered afferent
mechanoreceptor signaling as a result of joint pain and
inflammation may have influenced the shift of the COP
away from the limb with a surgically created osteo-
chondral fragment in the carpal joint during assessment of
the craniocaudal sway. The disruption of joint homeostasis
creates altered neural activity, resulting in disrupted mo-
tor control and movement patterns. The reduced ampli-
tudes of craniocaudal COP displacement in both limbs
with and without a surgically created osteochondral
fragment in the carpal joint of horses that were under-
going underwater treadmill exercise provided additional
evidence for the therapeutic potential of aquatic exercise.
Future studies are needed to determine the influence of
altered static postural control on dynamic balance char-
acteristics and performance capabilities in horses.
Although the exact mechanism for improved pos-
tural control after aquatic exercise could not be deter-
mined in the horses of the present study, postural sway
analysis did detect positive changes in balance control
in horses with carpal joint osteoarthritis. Postural sway
analysis is a sensitive diagnostic technique that may aid
in identifying potential proprioceptive or balance def-
cits associated with neuromuscular impairments asso-
ciated with joint pain or inflammation. Postural sway
analysis can also provide objective outcome variables
with which to monitor the effects that specific rehabili-
tation programs may have on postural stability. Results
of the present study have provided clinical insights into
the effects of altered visual input and stance positions
on a horse’s ability to maintain postural control. The destabilizing effects of altered vision and base-narrow
stance positions during quiet standing should be con-
dered when evaluating performance and compensa-
tory or adaptation strategies.

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