Kinematic and kinetic analyses of the gait of horses wearing novel legwear for variably limiting extension of the metacarpophalangeal joint

Lindsay B. St. George PhD
Brenna R. Pugliese DVM
Sarah J. Hobbs PhD
Abby L. Brisbois BS
Jonathan K. Sinclair PhD
Carl A. Kirker-Head VetMB

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From the Centre for Applied Sport and Exercise Sciences, University of Central Lancashire, Preston, PR1 2HE, England (St. George, Hobbs, Sinclair); and Orthopaedic Research Laboratory, Cummings School of Veterinary Medicine, Tufts University, North Grafton, MA 01536 (Pugliese, Brisbois, Kirker-Head). Dr. Pugliese's present address is the Department of Clinical Sciences, College of Veterinary Medicine, Cornell University, Ithaca, NY 14853.

Address correspondence to Dr. Kirker-Head (carl.kirker-head@tufts.edu).

OBJECTIVE

To investigate the effects of novel legwear designed to limit metacarpophalangeal joint (MCPJ) extension and redirect loading forces from the flexor apparatus through analyses of 2-D kinematic and kinetic data.

ANIMALS

6 adult horses without musculoskeletal disease.

PROCEDURES

Horses were subjected to 4 treatments: control (no legwear), inactive legwear (unlimited legwear extension), and active legwear with mild (30°) and moderate (20°) legwear extension limitation. Two-dimensional kinematic data were collected for the right forelimb (FL) during walk and trot and from leading and trailing FLs during canter on a treadmill. Ground reaction force (GRF) data were collected from FLs during overground walk and trot. Peak MCPJ angle and angular velocity were calculated from kinematic data, and peak force and average loading rate were calculated from vertical GRF data during the stance phase of the gait. Interactions between gait and treatment were determined via ANOVA.

RESULTS

Interactions between gait and treatment for peak MCPJ angle were significant. Significant reductions in MCPJ angle were noted between the control treatment and legwear with moderate extension limitation for trot and canter (leading and trailing FL) and between inactive legwear and legwear with moderate extension limitation for trot and leading FL during canter. Interactions among peak MCPJ angular velocity, peak vertical GRF, and average loading rate of the vertical GRF showed nonsignificance.

CONCLUSIONS AND CLINICAL RELEVANCE

Significant reductions in MCPJ extension without significant alterations to peak vertical GRF suggested the legwear's ability to redistribute internal forces. Findings suggested that the legwear may be beneficial for horses rehabilitating from flexor apparatus injuries. (*Am J Vet Res* 2021;82:48–54)

Legwear (eg, sport boots and bandages), often placed on the distal portions of the FLs of horses, is believed to provide support to the flexor apparatus by limiting extension of the MCPJ, which subsequently decreases the damaging effects of peak load and strains on the flexor apparatus.[1–5] Legwear may also have energy-absorbing properties that attenuate impact shock, thus protecting the structures of the distal portion of a limb.[3,4,6,7] In 1 study,[6] commercially available sport boots were found to increase energy absorption capacity in the hind limbs from cadaveric horses by up to 26%. In another study,[1] however, the same sport boot applied to the FL provided no significant resistance to MCPJ extension during limb loading. Loading the limbs from cadaveric horses at rates comparable to those for physiologic loading represents a major limitation of in vitro studies,[1,6] and only 1 publication[5] addressed the effect of commercially available legwear on MCPJ extension in vivo, wherein marked reductions in maximum MCPJ extension occurred during walk and trot. Drawing definitive conclusions on the effectiveness of legwear from these previous studies[1,5,6] is, therefore, problematic because study limitations and differences in study protocols resulted in conflicting findings. Because legwear use in equestrian athletic activities is widespread, further in vivo studies are required to better characterize legwear effectiveness for limiting MCPJ extension and, if legwear is effective, to determine whether it could be used to prevent or treat injury to the flexor apparatus.

ABBREVIATIONS

$\text{Active}_{\text{mild}(30^\circ)}$	Mild legwear extension limitation (30° extension)
$\text{Active}_{\text{mod}(20^\circ)}$	Moderate legwear extension limitation (20° extension)
ALR	Average loading rate of the vertical ground reaction force
FL	Forelimb
GRF	Ground reaction force
GRF_{max}	Peak vertical ground reaction force
Hoof impact_{50}	Hoof impact after 50 milliseconds
MCIII	Third metacarpal bone
MCPJ	Metacarpophalangeal joint
η_p^2	Partial êta-squared

A recent study[8] describes novel legwear[a] that was designed to mechanically and variably limit MCPJ extension through an adjustable stop mechanism. Legwear in an activated state sustained loading during stance for both in-stall activities and treadmill exercises, and mechanical limitation of MCPJ extension was postulated to have decreased peak load and torque on the flexor apparatus.[8]

The objective of the study reported here was to confirm the results of the previous study[8] by evaluating the effect of the legwear on MCPJ extension during walk, trot, and canter on a treadmill, by use of 2-D kinematic data, and the loading patterns of the FL during overground walk and trot, by use of a force plate. The legwear (vs no legwear) was hypothesized to be able to effectively limit MCPJ extension.

Materials and Methods

Animals

Six horses (mean [SD] age, 11.00 [5.22] years; body weight, 575.67 [61.78] kg; height, 1.64 [0.07] m) were used in this study. Each horse was visually assessed by a veterinarian (CAK-H) for musculoskeletal soundness with the American Association of Equine Practitioners' lameness scale[9] and with nuclear scintigraphy, ultrasonography, and radiography of the FLs to confirm the absence of any preexisting musculoskeletal disease. Approval for this study was granted by the Tufts University Institutional Animal Care and Use Committee (protocol No. G2014-13).

Prior to testing, horses were regularly trained on a treadmill[b] for a mean (SD) of 8.92 (3.51) months and habituated to the legwear for a mean of 7.83 (3.20) months during overground (in-hand) and treadmill exercise. The horses had similar exercise regimens to reasonably standardize physical fitness among the horses.

Legwear

The legwear[a] was applied to the distal portion of each FL. Each legwear piece had an upper and lower hemicircumferential cuff that was constructed of glass-impregnated polymer and affixed to an aircraft-grade aluminum scaffold. The cuffs were connected by aluminum side bars to a hinge with a laterally positioned titanium adjustable stop system, which could be manually adjusted to limit hinge range of motion and potentially MCPJ extension.

Under each cuff, an outer layer of firm polyurethane and inner layer of polymeric padding were molded to fit the legwear snugly and cushion the FL. Each cuff abutted soft tissues associated with the dorsal, medial, and lateral aspects of the MCIII (cannon) region (upper cuff) and the full circumference of the proximal interphalangeal (pastern) region (lower cuff). Importantly, the upper cuff avoided contact with the flexor apparatus. Hook-and-loop fasteners reinforced with buckled straps ensured secure and intimate contact between the padding and FL, such that the activated legwear could restrict MCPJ extension while minimizing motion of the legwear relative to the limb.

The legwear in the active state was designed to limit MCPJ extension, whereas the legwear in the inactive state was designed to permit unlimited MCPJ extension. Activated legwear may be applied with $\text{active}_{\text{mild(30)}}$, $\text{active}_{\text{mod(20°)}}$, or maximal (10° legwear extension) attenuation of legwear extension. When the legwear was activated through the adjustable stop, the lower cuff engaged the immovable stop on the upper cuff to create equal and opposite force vectors occurring partway through extension of the MCPJ during FL loading.

Engagement of the stop system (collectively includes adjustable and immovable stops) was intended to effectively create a truss between the upper (cannon region) and lower (pastern region) cuffs. The truss provided resistive torque against MCPJ extension without abruptly halting extension by mildly compressing the padding and permitting controlled motion of the legwear relative to the FL. Reaction loads from this resistive torque were then transmitted by the cuffs to the FL. At each end of the truss, one force element was parallel and another was perpendicular to the longitudinal axes of both the cannon and pastern regions.

Data acquisition

Kinematic (motion) data—Prior to data collection, each horse without legwear completed a 20-minute warm-up without legwear that consisted of a walk, trot, and canter on the treadmill. Spherical, retroreflective, motion-capture markers[c] (diameter, 6.4 to 12.7 mm) were applied to the medial aspect of the left FL and lateral aspect of the right FL at the following anatomic locations, which were used to collectively define the MCIII, pastern, and hoof segments: at the proximal end of the MCIII (just distal to the carpometacarpal joint at the dorsalmost limit of the articulation between the head of the second or fourth metacarpal bone and MCIII), MCPJ center of rotation, distal interphalangeal joint center of rotation, and dorsolateral hoof wall (just proximal to the horseshoe nails; **Figure 1**). Radiographs aided the accurate identification of the proximal end of the MCIII and centers of rotation for the MCPJ and distal interphalangeal joint. Motion-capture markers were also placed palmar to the marker at the proximal end of the MCIII, palmar to the marker at the MCPJ center of rotation, proximal to the coronary band (aligned with the dorsal aspect of the hoof wall), and on the dorsal aspect of the hoof wall proximal to the horseshoe nails. The markers were referenced to the anatomic landmarks in the static trial and then used to track the movement of limb segments during dynamic trials on the basis of the calibrated anatomic systems technique.[10,11]

Calibration of the camera system was conducted with a cube of known dimensions (0.18 X 0.125 m, in sagittal plane) placed on the treadmill at the approximate area of analysis for the hoof strike of the right and left FL. Separate 1-second videos of the cube at

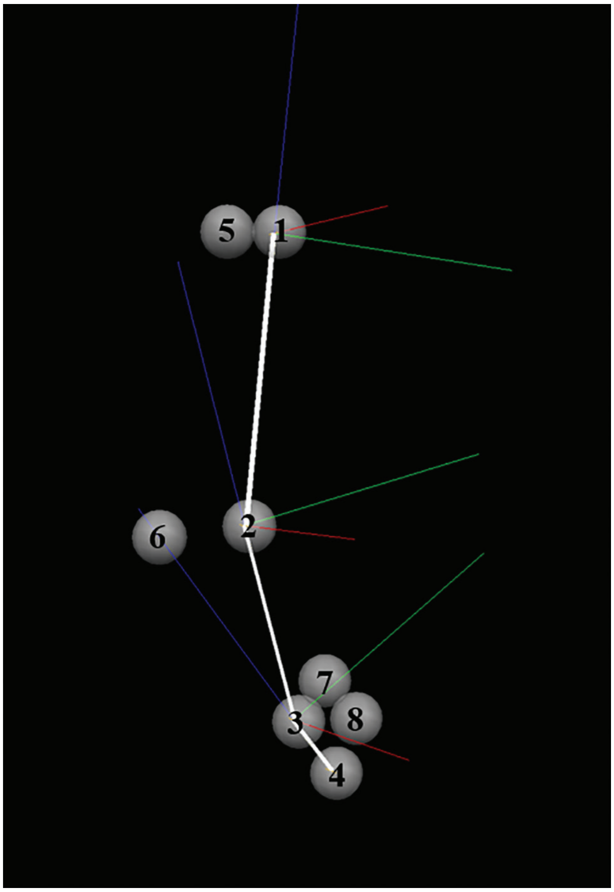

Figure 1—Stylized image showing the locations of the retroreflective markers placed on the distal portion of a horse's FL for kinematic data collection. Third metacarpal, pastern, and hoof segments are indicated by white lines. Red, green, and blue lines indicate the mediolateral, anterior-posterior, and inferior-superior (vertical) axes, respectively, of the segment coordinate systems for each segment. 1 = Proximal end of MCIII. 2 = MCPJ center of rotation. 3 = Distal interphalangeal joint center of rotation. 4 = Dorsolateral hoof wall (just proximal to the horseshoe nails). 5 = Opposite and palmar to the marker at the proximal end of the MCIII. 6 = Opposite and palmar to the marker at the MCPJ center of rotation. 7 = Proximal to the coronary band, aligned with the dorsal aspect of the hoof wall. 8 = Dorsal aspect of the hoof wall, proximal to the horseshoe nails.

each hoof-strike location were recorded with a high-speed camera[d] set to the same zoom setting (setting 26) as that used for the study. Calibration videos were uploaded to motion-analysis software,[e] where cube dimensions and location in space were used to create a calibration file for both FLs of each horse. Calibration resulted in mean (SD) angular digitizing accuracy of 0.76° (0.58°) and linear accuracy of 5.2 (3.2) mm.

Kinematic data were collected with the high-speed camera in the sagittal plane at 480 Hz during walk, trot, and canter on the treadmill, with horses subjected to the first of 4 conditions: no legwear (control), inactive legwear (unlimited legwear extension), and 2 active legwear states ($\text{active}_{\text{mild}[30^\circ]}$ and $\text{active}_{\text{mod}[20^\circ]}$). The active states were designed to limit MCPJ extension with mild (30°) or moderate (20°) attenuation of legwear extension. The camera was positioned perpendicular to the long axis of the treadmill to capture a sagittal image of the ambulating horse. The center of the camera's field of view was at the height of the MCPJ center of rotation for each horse to accommodate the height of the treadmill.

Static (standing) trials without legwear were conducted to collect data from both FLs, and the collected data were then used to create an FL model for each dynamic (treadmill walk, trot, and canter) trial. Kinematic data for each dynamic trial were collected for a 30-second period; gait order was standardized (in order: walk, trot, and canter), and treatment (control [no legwear], inactive, $\text{active}_{\text{mild}[30^\circ]}$, and $\text{active}_{\text{mod}[20^\circ]}$) was randomized.[f] A 5-minute break was allotted between each 30-second period. Treadmill speed was standardized for each gait and horse through predetermined dimensionless speeds.[8,12] Owing to assumed symmetry of walk and trot gaits, only data from the right FL were analyzed for those gaits. For canter, however, data from left and right FLs (leading and trailing FLs and vice versa) were collected. Horses were permitted to canter on their preferred lead limb.

Video recordings were imported into motion-analysis software[e] for digitization. The position of each marker was tracked and captured for the entire stance phase of the gait for each trial. Data were then exported to an electronic spreadsheet,[g] converted to an appropriate format, and imported into a software package[h] specific for kinematic data analysis.

Kinetic (force) data—Kinetic data were collected in a separate series of tests during walk and trot overground (vs a treadmill). Horses were led by an experienced handler over a piezoelectric force plate[i] embedded in a rubber track and covered by high-density rubber material. Horses were acclimated to the testing routine prior to data collection. Data from both FLs were collected at 1,000 Hz with kinetic data acquisition software[j]; gait order (walk, then trot) was standardized, and treatment (control [no legwear], inactive, $\text{active}_{\text{mild}[30^\circ]}$, and $\text{active}_{\text{mod}[20^\circ]}$) order was randomized.[f] Three light diodes were positioned laterally on the track at regular intervals to measure the speed of each horse. A trial was successful when the entire hoof of an FL contacted the force plate without simultaneous contact by a hoof of another limb and absolute speed was within 0.08 m/s of the speed required for each horse to achieve the dimensionless speed for each gait. Six successful trials were obtained for each gait and treatment.

Data analysis

Kinematic data—A model of MCIII, pastern, and hoof segments was created by use of static files from the left and right FL of each horse with the control treatment. The model was applied to the dynamic trials for all gaits and legwear treatments. Data from 6 strides for each combination of gait and treatment were interpolated and smoothed by use of a low-pass filter (zero-lag, Butterworth fourth order) with a cutoff frequency of 12 Hz, which was validated through residual analysis. A segment coordinate system was defined for each FL segment (MCIII, pastern, and hoof) on the basis of the laboratory coordinate system. Angle of the MCPJ was calculated as the angle between the MCIII and pastern segments. Joint angles were measured in the sagittal plane, in which flexion and extension were defined as rotation about the x-axis of the segment coordinate system. An angle of 0° was observed when the MCIII and pastern segments were aligned; therefore, a positive angle indicated the amount of extension. Angular velocity of the MCPJ was calculated as the angular velocity of the pastern segment relative to the MCIII segment in the sagittal plane.

Hoof impact was identified with the method described by Hobbs et al[13] and defined as the midpoint between vertical velocity minima and vertical acceleration maxima of the distal interphalangeal joint marker. Hoof liftoff was identified with planar angles of the MCIII and pastern segments, in accordance with the method described by Holt et al.[14] Peak MCPJ angle and angular velocity were defined as the maximum value between hoof impact and hoof liftoff events from the continuous MCPJ angle and angular velocity data. Two MCPJ angle peaks were identified during a walk. However, because the second peak had the largest MCPJ angle in most recordings, the second peak was included in the analysis for consistency.

Kinetic data—Vertical GRF data were analyzed with acquisition software,[j] which automatically detected hoof impact and hoof liftoff events. Data were smoothed prior to their detection by use of a window length of 0.003 seconds, corresponding to 3 points at 1,000 Hz. Hoof impact was detected as the first data point where the GRF curve surpassed 0 N, and hoof liftoff was detected at the point after GRF_{max}, where the falling slope of the GRF curve between consecutive data points was 0 N. To ensure that impact-related deceleration peaks were excluded from the calculations, a hoof $impact_{50}$ event was detected in accordance with the duration of impact deceleration forces reported by Gustås et al.[15] Peak vertical GRF was calculated as the maximum value between hoof $impact_{50}$ and hoof liftoff events and normalized to each horse's body weight. The ALR of the GRF curve was calculated by dividing GRF_{max} by the time between hoof $impact_{50}$ and GRF_{max} events. Two vertical loading peaks were consistently detected in the data set obtained from a walk, and ALR was calculated from the first vertical loading peak during the braking phase. The GRF_{max} was consistently detected as the second loading peak during the propulsive phase for a walk and, therefore, was exported for analysis. Across the data set, the first loading peak was detected as the GRF_{max} in 2 walk trials; therefore, these were considered outliers and not included in the analysis. Kinematic and kinetic data were exported to an electronic spreadsheet[g] for statistical analysis.

Statistical analysis

Descriptive statistics were calculated for all variables for each combination of gait and treatment. The authors were blinded to the gait and treatment during statistical analysis. Repeated-measures ANOVA was performed for each kinematic and kinetic variable. Post hoc comparisons were investigated with a Bonferroni correction when significant main effects were identified. Statistical analyses were performed with statistical software.[k] Values of $P < 0.05$ were considered significant.

Results

Kinematic data

Mean (SD) peak MCPJ angle and peak angular velocity for all combinations of gaits and treatments are summarized (**Table 1; Supplementary Figures S1 and S2**, available at: avmajournals.avma.org/doi/suppl/10.2460/ajvr.82.1.48). Significant interactions between gait and treatment were found for peak MCPJ angle ($F9,45 = 3.06$; $P < 0.01$; $\eta_p^2 = 0.38$). Mean differences in MCPJ angle were significant between the control and $active_{mod(20°)}$ treatments and between the inactive and $active_{mod(20°)}$ treatments for trot and in the leading FL for canter **(Table 2)**. Mean differences in MCPJ angle were also significant between control and $active_{mod(20°)}$ treatments in the trailing FL for canter. No significant interactions between gait and treatment were found for peak MCPJ angular velocity ($F9,45 = 1.69$; $\eta_p^2 = 0.25$).

Table 1—Mean ± SD peak MCPJ angle and peak angular velocity for various combinations of gaits and treatments for 6 adult horses without musculoskeletal disease and with (inactive or active) or without (control) novel legwear designed to limit extension of the MCPJ.

		Treatment			
MCPJ variable	**Gait**	**Control**	**Inactive**	**$Active_{mild(30°)}$**	**$Active_{mod(20°)}$**
Peak angle (°)	Walk	40.02 ± 4.40	40.38 ± 4.50	39.63 ± 4.19	39.20 ± 4.63
	Trot	52.21 ± 4.13	52.15 ± 4.31	50.42 ± 4.89	49.92 ± 4.28
	Canter LF	52.47 ± 7.97	52.53 ± 7.17	50.55 ± 8.09	49.91 ± 7.97
	Canter TF	57.86 ± 4.49	57.96 ± 4.10	56.35 ± 3.72	55.66 ± 3.60
Peak angular velocity (°/s)	Walk	200.03 ± 34.82	216.36 ± 48.56	209.45 ± 41.63	209.97 ± 27.97
	Trot	309.39 ± 52.72	318.57 ± 53.37	296.54 ± 56.75	296.59 ± 51.61
	Canter LF	432.28 ± 53.97	437.35 ± 55.40	419.12 ± 59.53	402.86 ± 45.09
	Canter TF	501.64 ± 54.15	524.97 ± 76.45	493.93 ± 55.43	486.65 ± 54.06

Table 2—Mean difference and pairwise comparisons of peak MCPJ angles between treatments for each gait for the horses of Table 1.

Gait	Variable	Control – inactive	Control – active$_{\text{mild}(30^\circ)}$	Control – active$_{\text{mod}(20^\circ)}$	Inactive – active$_{\text{mild}(30^\circ)}$	Inactive – active$_{\text{mod}(20^\circ)}$	Active$_{\text{mod}(20^\circ)}$ – active$_{\text{mild}(30^\circ)}$
Walk	Difference	–0.35	0.39	0.83	0.75	1.18	–0.44
	95% CI	–2.04 to 1.33	–0.92 to 1.70	–1.03 to 2.68	–0.87 to 2.36	–0.44 to 2.80	–1.70 to 0.82
	P value	> 0.99	> 0.99	0.71	0.65	0.17	> 0.99
Trot	Difference	0.06	1.79	2.29	1.73	2.23	-0.50
	95% CI	–1.38 to 1.51	–0.23 to 3.82	0.85 to 3.74	–0.30 to 3.76	0.83 to 3.63	–2.09 to 1.09
	P value	> 0.99	0.08	0.01	0.09	0.01	> 0.99
Canter LF	Difference	–0.07	1.91	2.55	1.98	2.62	–0.64
	95% CI	–2.45 to 2.32	–0.27 to 4.09	0.95 to 4.16	–0.72 to 4.67	0.09 to 5.15	–1.38 to 0.10
	P value	0.57	0.08	0.01	0.16	0.04	0.09
Canter TF	Difference	–0.10	1.51	2.20	1.61	2.30	–0.69
	95% CI	–2.63 to 2.43	–0.63 to 3.65	0.39 to 4.01	–1.64 to 4.86	–0.39 to 4.98	–1.69 to 0.31
	P value	> 0.99	0.19	0.02	0.54	0.09	0.20

Values of $P < 0.05$ were considered significant.

Table 3—Mean ± SD for GRF$_{max}$ and ALR for the horses of Table 1.

		Treatment			
Variable	**Gait**	**Control**	**Inactive**	**Active$_{\text{mild}(30^\circ)}$**	**Active$_{\text{mod}(20^\circ)}$**
GRF$_{max}$ (N/kg)	Walk	6.59 ± 0.26	6.62 ± 0.27	6.64 ± 0.26	6.66 ± 0.22
	Trot	9.85 ± 0.47	9.87 ± 0.46	9.97 ± 0.70	10.01 ± 0.69
ALR (N/kg•s)	Walk	14.72 ± 2.08	14.94 ± 1.89	14.79 ± 2.15	14.82 ± 1.96
	Trot	34.31 ± 5.45	34.73 ± 5.82	34.66 ± 4.49	34.95 ± 5.03

Kinetic data

Mean (SD) for GRF$_{max}$ and ALR for all combinations of gaits and treatments are summarized **(Table 3)**. No significant interactions between gait and treatment were found for GRF$_{max}$ ($F3,15 = 1.09$; $\eta_p^2 = 0.18$) and ALR ($F3,15 = 0.27$; $\eta_p^2 = 0.05$).

Discussion

The objective of this study was to investigate the effect of novel rehabilitative legwear on MCPJ movement and FL loading in horses by use of 2-D kinematic data and force plate data, respectively. The legwear in the active$_{\text{mod}(20^\circ)}$ state significantly limited MCPJ extension during the stance phase of the gait at trot and canter. However, the legwear did not significantly affect peak MCPJ angle during walk or peak MCPJ angular velocity, GRF$_{max}$, or ALR at any gait. Thus, these findings supported the hypothesis that the active legwear limited MCPJ extension, although not for all gaits and conditions.

The legwear in the active$_{\text{mod}(20^\circ)}$ state may have significantly limited MCPJ extension because this state produced a smaller legwear extension angle than the active$_{\text{mild }(30^\circ)}$ and inactive states through earlier engagement of the adjustable stop, which prevented any further movement between the upper and lower cuffs. Thus, the active$_{\text{mod}(20^\circ)}$ state provided more resistance to MCPJ extension during the stance phase, similar to previous findings.[1] As in that study[1] involving the evaluation of support bandages and sport boots, the legwear evaluated in the present study also did not limit MCPJ extension at walk with an MCPJ extension angle < 45° (ie, active$_{\text{mild}[30^\circ]}$ and active$_{\text{mod}[20^\circ]}$); significant differences between these states at a walk may not have been observed because MCPJ extension at that gait is typically < 45°.[16,17] Nonetheless, a nonsignificant reduction in mean MCPJ angle was observed in this study between active$_{\text{mild}(30^\circ)}$ and active$_{\text{mod}(20^\circ)}$ treatments across all gaits. In a previous study,[8] telemetric force sensors were affixed to the loading surface of the legwear's adjustable stop to examine load redistribution, and the active$_{\text{mod}(20^\circ)}$ state resulted in significantly higher peak load, compared with peak load for the active$_{\text{mild}(30^\circ)}$ state during walk, trot, and canter and during in-stall walking (vs standing). Thus, nonsignificant reductions in mean MCPJ angle in active legwear states may still be clinically important, given the reported load redistribution.[8] Furthermore, in a horse with an injured flexor apparatus, MCPJ extension may increase beyond 45° when extension torque cannot be resisted[18]; therefore, even mild mechanical resistance (active$_{\text{mild}[30^\circ]}$ state) may be more beneficial for an injured horse than for a sound horse. Further work, however, is required to investigate the benefits of this legwear for horses rehabilitating from a flexor apparatus injury.

Peak MCPJ angles in the leading FL and trailing FL during canter differed among treatments, with individual differences similar to those reported in studies[19,20] that describe functional differences during canter. Both leading and trailing FLs had a significant reduction in peak MCPJ angle of approximately 2° to 3° between control and active$_{\text{mod}(20^\circ)}$ treatments. A similar reduction of 2° to 3° was found at trot, and peak MCPJ angle was similar to that of the leading FL at canter. Although this reduction in MCPJ extension may be considered small, Kicker et al[5] suggest that a reduction of 1° may result in tendon load reductions of approximately 200 N for a 500-kg trotting horse when inverse dynamics are applied in accordance with Meershoek and Lanovaz[21] and Meershoek et al.[22]

The magnitude and timing of GRF experienced by the limb determine the load experienced by musculoskeletal structures,[23] and a linear MCPJ angle-force relationship has been described.[24] This linear angle-force relationship is dependent on the calibration of vertical limb force and MCPJ angle data for individual horses during low-speed gaits.[23–25] Although kinematic and kinetic data were collected separately in the present study, the significant reduction in peak MCPJ extension with legwear in the $\text{active}_{\text{mod(20°)}}$ state observed during trot, with no change in the rate of MCPJ extension (peak angular velocity) nor in vertical limb loading (ALR and GRF_{max}), implied that the legwear in the $\text{active}_{\text{mod(20°)}}$ state resulted in a redistribution of force within the internal structures of the distal portion of the FL.[5] This apparent redistribution of force is supported by previously reported[8] findings in which the $\text{active}_{\text{mod(20°)}}$ state had a significantly greater peak legwear redirected load, compared with the $\text{active}_{\text{mild (30°)}}$ state during walk, trot, and canter. This led the authors of that study[8] to suggest that increasingly limiting MCPJ extension induces a proportional increase in the redirection of vertical loading forces from the flexor apparatus principally to the dorsal aspects of the cannon and pastern regions. However, the relative redistribution of reduced force among the internal structures of the flexor apparatus that can be affected (eg, superficial digital flexor tendon, deep digital flexor tendon, and suspensory ligament) is currently unconfirmed.

Mean peak MCPJ angles were similar for control and inactive treatments at trot and canter in the leading FL, which may explain why significant differences were found between these treatments and $\text{active}_{\text{mod(20°)}}$. Most horses (3 to 5, depending on gait) had slightly higher mean maximum MCPJ extension with the inactive treatment, compared with the control treatment, which may indicate that the weight of the legwear in the present study subtly influenced MCPJ rotation. This was also observed for GRF_{max} data at walk and trot, which exhibited slight but nonsignificant increases during legwear conditions. This finding was not surprising because speed is the main factor influencing the kinematics and kinetics of gait,[26] with velocity-dependent stance and swing duration, peak vertical force, and vertical impulse as other factors.[24,27,28] Because speed was standardized for each horse, nonsignificant differences in GRF_{max} were expected among horses and suggested that the slight increases in GRF_{max} observed with inactive and active legwear treatments possibly occurred also because of added weight of the legwear. However, the legwear would not be worn by a patient in the inactive state; the inactive state was included in the present study only for comparison with control and active legwear treatments.

In the present study, kinematic data were collected during walk, trot, and canter on a treadmill from sound horses; future work is, therefore, required to confirm whether findings from this study are applicable to overground locomotion and for horses with injuries of the flexor apparatus. This information will further determine the effectiveness of this legwear for rehabilitative purposes. Additionally, horses had a long habituation period (mean, 7.83 months) to the legwear prior to data collection; therefore, any proprioceptive effects of the legwear were unlikely to be observed in this study.[29,30] Future studies could include horses that are not habituated to the legwear, although its clinical use is intended for the duration of the rehabilitative period. Kinematic and kinetic data were collected separately in the present study, which prevented direct comparison of MCPJ kinematics and limb-force data. Therefore, further work is required to simultaneously evaluate kinematic and kinetic plus electromyographic data for the entire FL to fully examine the rehabilitative effectiveness of the legwear.

Findings from the present study revealed that the novel legwear limited extension of the MCPJ at faster gaits when the $\text{active}_{\text{mod(20°)}}$ state was applied, implying a mechanical support effect. The legwear did not have a significant effect on MCPJ angular velocity, GRF_{max}, and ALR. However, significant reductions in MCPJ extension without significant alterations to GRF_{max} indicated the legwear's ability to redistribute internal forces, which was consistent with findings of a previous study[8] of the same legwear. The findings of the present study demonstrated a potential clinical application for the legwear, in which MCPJ extension can be selectively limited on the basis of the type and severity of the injury of the flexor apparatus and adjusted throughout rehabilitation.

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Footnotes

a. FastTrack prototype, Horsepower Technologies Inc, Lowell, Mass.
b. Equigym LLC, Lexington, Ky.
c. Traditional reflective markers, B&L Engineering, Santa Ana, Calif.
d. NEX-FS700R Super 35 Camcorder, Sony, New York, NY.
e. Proanalyst Lite Edition, Xcitex Inc, Woburn, Mass.
f. True random number service, Random.org, Randomness and Integrity Services Ltd, Dublin, Ireland. Available at: www.random.org. Accessed Jan 15, 2015.
g. Microsoft Corp, Redmond, Wash.
h. Visual 3D, C-Motion Inc, Germantown, Md.
i. Model Z4852, Kistler Instruments, Amherst, NY.
j. Acquire Canine/Equine Biomechanics Data Acquisition Program, version 7.33, Sharon Software Inc, Owosso, Mich.
k. IBM Corp, Armonk, NY.

References

1. Smith RKW, McGuigan M, Hyde J, et al. In vitro evaluation of nonrigid support systems for the equine metacarpophalangeal joint. *Equine Vet J* 2002;34:726–731.
2. Ramón T, Prades M, Armengou L, et al. Effects of athletic taping of the fetlock on distal limb mechanics. *Equine Vet J* 2004;36:764–768.
3. Crawford W, Vanderby R Jr, Neirby D, et al. The energy absorption capacity of equine support bandages. Part II: comparison between bandages from different materials. *Vet Comp Orthop Traumatol* 1990;1:10–17.
4. Crawford W, Vanderby R Jr, Neirby D, et al. The energy absorption capacity of equine support bandages. Part I: comparison between bandages placed in various configurations and tensions. *Vet Comp Orthop Traumatol* 1990;1:2–9.
5. Kicker CJ, Peham C, Girtler D, et al. Influence of support boots on fetlock joint angle of the forelimb of the horse at walk and trot. *Equine Vet J* 2004;36:769–771.
6. Balch O, Collier M, Brusewitz G, et al. Energy absorption capacity of commercial equine support boots. *Vet Comp Orthop Traumatol* 1998;11:173–177.
7. Kobluk C, Martinez del Campo L, Harvey-Fulton K, et al. A kinematic investigation of the effect of a cohesive elastic bandage on the gait of the exercising Thoroughbred racehorse, in *Proceedings*. 35th Annu Meet Am Assoc Equine Pract 1989;135–148.
8. Pugliese BR, Brisbois AL, Size KJ, et al. Biomechanical and wearability testing of novel legwear for variably limiting extension of the metacarpophalangeal joint of horses. *Am J Vet Res* 2021;82:39–47.
9. American Association of Equine Practitioners. Lameness exams: evaluating the lame horse. Available at: www.aaep.org/horsehealth/lameness-exams-evaluating-lame-horse. Accessed Apr 20, 2019.
10. Cappozzo A, Catani F, Della Croce U, et al. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech (Bristol, Avon)* 1995;10:171–178.
11. Hobbs SJ, Richards J, Matuszewski B, et al. Development and evaluation of a noninvasive marker cluster technique to assess three-dimensional kinematics of the distal portion of the forelimb in horses. *Am J Vet Res* 2006;67:1511–1518.
12. Alexander RM. Terrestrial locomotion. In: Alexander RM, Goldspink G, eds. *Mechanics and energetics of animal locomotion*. London: Chapman and Hall, 1977;168–203.
13. Hobbs SJ, Orlande O, Edmundson CJ, et al. Development of a method to identify foot strike on an arena surface: application to jump landing. *Comp Exerc Physiol* 2010;7:19–25.
14. Holt D, St George L, Clayton H, et al. A simple method for equine kinematic gait event detection. *Equine Vet J* 2017;49:688–691.
15. Gustås P, Johnston C, Drevemo S. Ground reaction force and hoof deceleration patterns on two different surfaces at the trot. *Equine Comp Exerc Physiol* 2006;3:209–216.
16. Back W, Schamhardt HC, Barneveld A. Are kinematics of the walk related to the locomotion of a warmblood horse at the trot? *Vet Q* 1996;18:S79–S84.
17. Hodson E, Clayton H, Lanovaz J. The hindlimb in walking horses: kinematics and ground reaction forces. *Equine Vet J* 2001;33:38–43.
18. Butcher MT, Ashley-Ross M. Fetlock joint kinematics differ with age in Thoroughbred racehorses. *J Biomech* 2002;35:563–571.
19. Merkens HW, Schamhardt HC, Hartman W. Ground reaction force patterns of Dutch Warmbloods at the canter. *Am J Vet Res* 1993;54:670–674.
20. Back W, Schamhardt HC, Barneveld A. Kinematic comparison of the leading and trailing fore and hindlimbs at the canter. *Equine Vet J Suppl* 1997;29:80–83.
21. Meershoek LS, Lanovaz JL. Sensitivity analysis and application to trotting of a noninvasive method to calculate flexor tendon forces in the equine forelimb. *Am J Vet Res* 2001;62:1594–1598.
22. Meershoek LS, Bogert AJ, Schamhardt HC. Model formulation and determination of in vitro parameters of a noninvasive method to calculate flexor tendon forces in the equine forelimb. *Am J Vet Res* 2001;62:1585–1593.
23. Witte TH, Knill K, Wilson AM. Determination of peak vertical ground reaction force from duty factor in the horse (*Equus caballus*). *J Exp Biol* 2004;207:3639–3648.
24. McGuigan MP, Wilson AM. The effect of gait and digital flexor muscle activation on limb compliance in the forelimb of the horse (*Equus caballus*). *J Exp Biol* 2003;206:1325–1336.
25. Bobbert MF, Álvarez CBG, van Weeren PR, et al. Validation of vertical ground reaction forces on individual limbs calculated from kinematics of horse locomotion. *J Exp Biol* 2007;210:1885–1896.
26. Weishaupt MA, Hogg HP, Auer JA, et al. Velocity-dependent changes of time, force and spatial parameters in warmblood horses walking and trotting on a treadmill. *Equine Vet J Suppl* 2010;42:530–537.
27. Dutto DJ, Hoyt DF, Cogger EA, et al. Ground reaction forces in horses trotting up an incline and on the level over a range of speeds. *J Exp Biol* 2004;207:3507–3514.
28. McLaughlin RM, Gaughan EM, Roush JK, et al. Effects of subject velocity on ground reaction force measurements and stance times in clinically normal horses at the walk and trot. *Am J Vet Res* 1996;57:7–11.
29. Clayton HM, Lavagnino M, Kaiser LJ, et al. Swing phase kinematic and kinetic response to weighting the hind pasterns. *Equine Vet J* 2011;43:210–215.
30. Clayton HM, Lavagnino M, Kaiser LJ, et al. Evaluation of biomechanical effects of four stimulation devices placed on the hind feet of trotting horses. *Am J Vet Res* 2011;72:1489–1495.