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Inertial measurement units are comparable to motion capture for measuring intersegmental spinal angular velocities in horses

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Objective
To compare inertial measurement unit (IMU)-derived intersegmental spinal motion data with measurements obtained from a marker-based motion-capture system.

Methods
4 horses were instrumented with custom marker clusters incorporating a 3-D–printed base designed to secure the IMU, ensuring both systems recorded data from the same anatomical location and orientation. A total of 3,737 paired time points across 37 gait cycles were analyzed. Agreement in intersegmental angular velocities across 3 planes of motion was evaluated using Bland-Altman analysis and intraclass correlation coefficients.

Results
Bland-Altman analysis demonstrated no significant systematic bias between methods. Intraclass correlation coefficients indicated excellent agreement in 7 of 9 comparisons (r = 0.964 to 0.991) and good agreement in the remaining 2 comparisons (r = 0.854 and 0.875).

Conclusions
IMUs provide a valid alternative to marker-based motion-capture systems for measuring intersegmental angular velocities in horses.

Clinical Relevance
Strong agreement between IMU and motion-capture data supports the use of IMUs for assessing topline function in nonlaboratory, clinically relevant settings.

Keywords: angular velocity, quality of motion, spinal motion, back pain, equine

In horses, a condition referred to as topline dysfunction can be characterized by paraspinal musculature spasticity, stiffness, weakness, and generalized pain.[1] Although this condition is widely recognized clinically, it has not been comprehensively described using biomechanical methods. Clinician surveys highlight a strong need for objective measures to improve the precision and accuracy of topline movement assessment.[2]

Noninvasive measurement of spinal motion in horses has traditionally involved using motion capture to track skin-fixed markers and then calculating translational and rotational displacements from the data.[3–7] Recently, the analysis of intersegmental angular velocity has shown promise in assessing quality of movement of the topline of the horse.[1] In human populations, angular velocity has proved useful in distinguishing between individuals with and without a clinical condition[8–10] and in evaluating the quality of movement while performing complex tasks.[11]

Angular displacement describes details of the changing relationship between body segments as they move from one position to another. Angular velocity indicates the rate at which the positional changes occur, and this provides an objective measure of quality of movement.[12] Repeated evaluations

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overcome some of the challenges of observational assessments by providing clinicians with quantitative information to track progress or deterioration during recovery from injury.[13] In human patients, angular velocity has been shown to be a more sensitive method to discriminate between individuals with and without back pain as well as assess the quality of movement in individuals with low-back pain.[8–10] Therefore, spinal intersegmental angular velocity is a promising noninvasive method to assess quality of spinal movement, which could be implemented in the assessment of horses. A recent publication reported large differences in angular velocities between spinal segments in all 3 planes of motion at the walk and trot between lame and sound horses.[1]

The majority of 3-D motion analysis studies have used cameras to track markers affixed to the body as it moves through the camera's field of view. Motion-capture systems are expensive, and data collection is confined to a calibrated image space that is usually within a laboratory. An alternative to marker-based systems is the use of inertial measurement units (IMUs), which can be used outside of the laboratory to assess motion over any terrain or in any environment.[9] The primary limitation of IMUs is that their output is referenced to a local coordinate system, within which multiple sensors can determine clinically relevant segmental relationships. Assessment of 3-D angular velocity data offers advantages over angular displacements, which are fraught with technical challenges, such as signal drift, when using IMUs. As a result, some researchers prefer to use gyroscopic data from the IMUs to measure angular velocity directly as a measure of quality of movement rather than the derived angular displacement.[14,15]

Inertial measurement units have been utilized quite extensively in biomechanical research in horses. To date, the only output measures reported in equine studies[16] use complex processing to extrapolate displacement data without consideration of angular velocity calculated from the accelerometric data or measured directly from the gyroscopic data. The purpose of this study was to determine whether IMU-derived angular velocity could be used as a viable alternative to the reference standard of optical motion capture when describing intersegmental spinal motion in horses. If successful, this would facilitate assessment of spinal motion on any surface or terrain, in any environment, and under different exercise conditions. Our hypothesis is that the intersegmental angular velocity reported by gyroscopes within IMUs would have a good level of agreement with that calculated by a camera motion-capture system in all motion planes between specific segments of the topline of the horse.

Methods

This study was approved by the IACUC of the University of Tennessee (protocol No. 2659). Four horses owned and maintained by the University of Tennessee Veterinary Research and Education Center were chosen and defined as being sound based on lameness evaluations using the Equinosis Q quantitative analysis system and subjective visual assessment by a board-certified specialist in equine sports medicine and rehabilitation (TU). Horses were instrumented with motion-capture tracking markers and Avanti IMU sensors (Delsys).

Horses were instrumented with 4 marker clusters that had a 3-D–printed base with 4 noncolinear, 9-mm reflective tracking markers on rigid stems and an area designed for insertion of the IMU **(Figure 1)**. This arrangement ensured that the marker cluster and the IMU were recording data from the same anatomic location. Each cluster base had malleable struts that could be custom fit to each horse. Clusters were attached with adhesive to the dorsal midline of the horse at the 7th thoracic (cranial thoracic [CRT]), 15th thoracic (caudal thoracic [CDT]), and 3rd lumbar (lumbar [LUM]) dorsal spinous processes and to the tuber sacrale (sacral [SAC]). Single markers

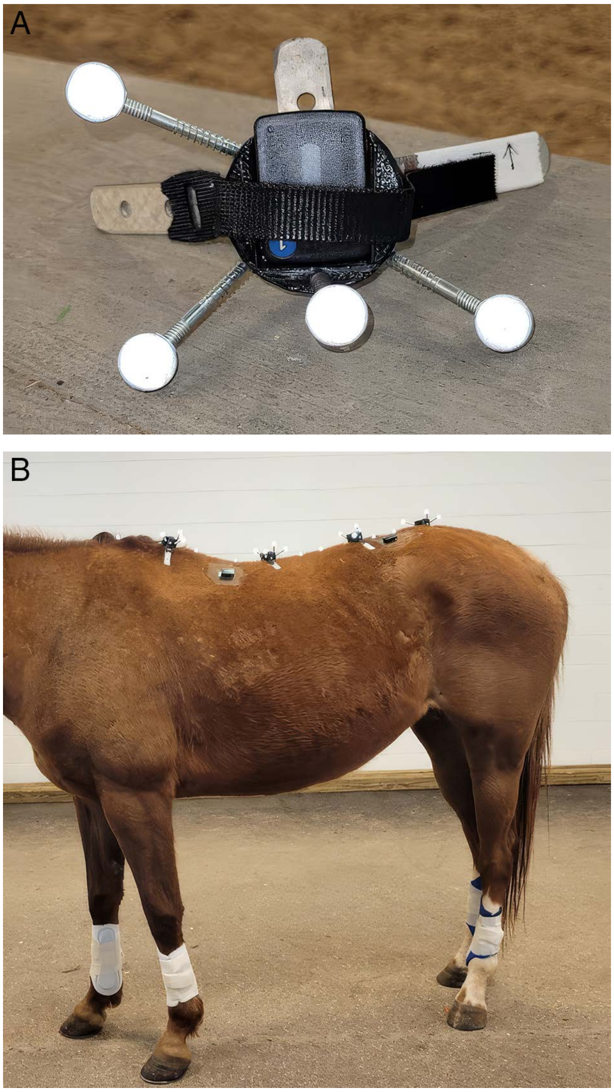

Figure 1—A—Custom 3-D–printed base of rigid cluster with insertable slot for inertial measurement unit (IMU). B—Lateral view of horse showing the anatomic locations of marker clusters, anatomic markers, and inertial measurement unit.

were attached directly to the skin over the poll; the 4th, 11th, 13th, and 18th thoracic dorsal spinous processes; the 1st and 6th LUM dorsal spinous processes; the lumbosacral space; and the 1st coccygeal vertebra. An IMU attached to the lateral aspect of the metacarpal and metatarsal regions using modified leg wraps was used for gait event identification.

Prior to data collection, the 12 motion-capture cameras (Vantage 5; Vicon) were calibrated per manufacturer recommendations, with less than 1 mm in residual error reported. Cameras were positioned around the defined capture volume measuring 8 X 4 X 2 m, with 4 cameras on each long side and 2 at either end of the capture volume.

To individualize the model to each horse, a static standing trial was collected. Horses stood square with a neutral head and neck position in the middle of the capture volume. Care was taken to ensure horses were fully weight-bearing on all 4 limbs with their spine as parallel to the long axis of the capture volume as possible. This was used to determine the position and orientation of the spinal segments using the calibrated anatomical systems technique (CAST).[17]

Each horse performed 5 repetitions at trot in hand starting a minimum of 10 m prior to the capture volume to ensure they had reached a steady pace before reaching the active area data collection. Motion-capture cameras were calibrated using manufacturer recommendations, with less than 1 mm in residual error reported. Horses were allowed to travel at their own preferred speed, and the same handler was used for all horses throughout data collection to promote consistency of movement. This resulted in a minimum of 3 complete gait cycles obtained within the capture volume for each trial.

Data from the IMU sensors were collected through Nexus software (version 2.16, Vicon). The IMU (148 Hz) and marker (100 Hz) data were collected synchronously, exported to Visual3D (version 2024.10.4, HAS Motion), and filtered using a 15-Hz low-pass filter. For calibration, the angular velocity signals from each IMU were zeroed before attachment to the horse. Raw signals from the gyroscopes were then exported and filtered using a 15-Hz low-pass filter, and the relative angular velocities between the local coordinate system of each sensor were used to calculate the intersegmental angular velocities. Intersegmental angular velocities were calculated in the sagittal, dorsal, and transverse planes from both the marker and the IMU data as a

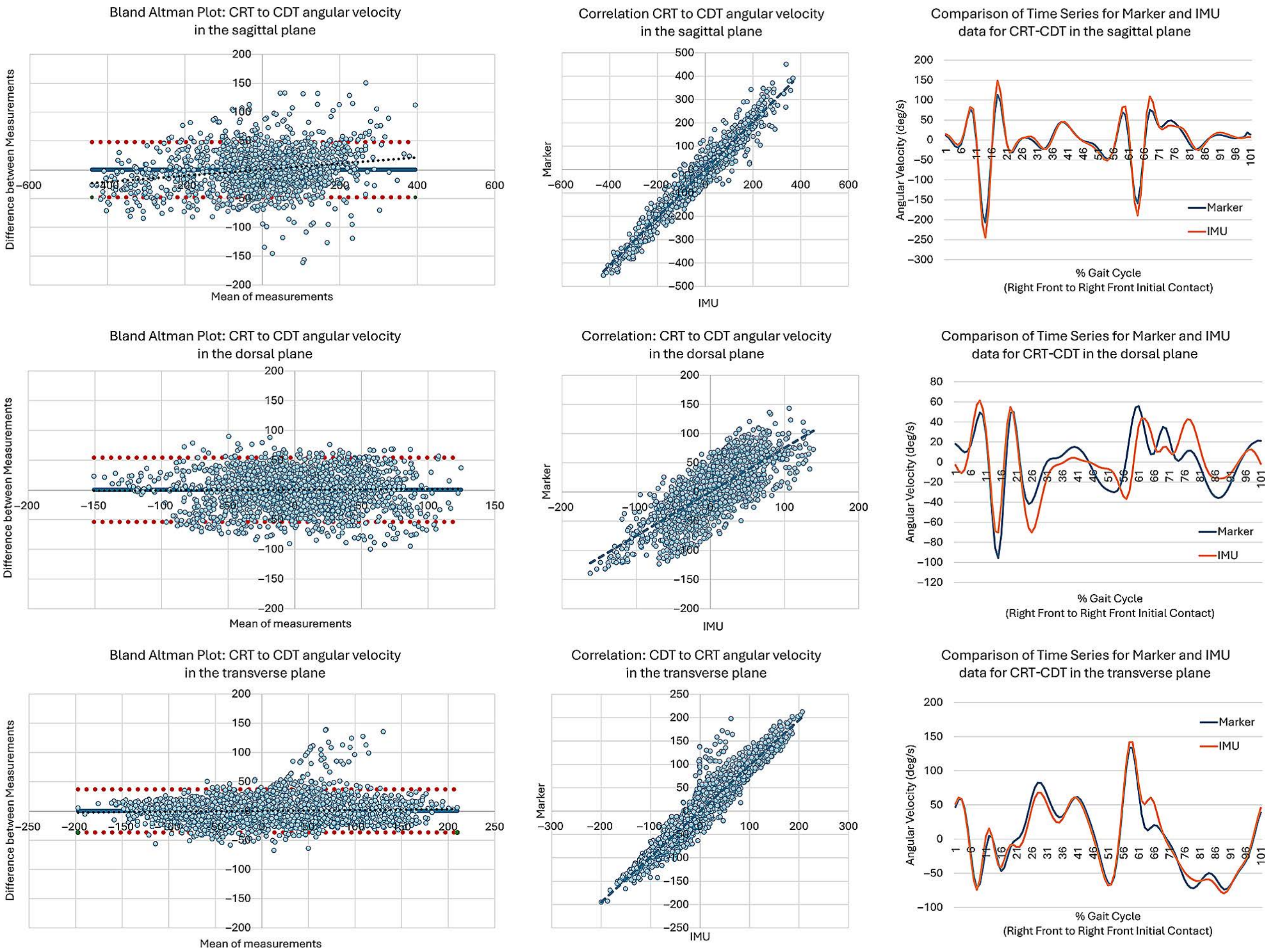

Figure 2—Bland-Altman plots (left), correlations (center), and comparison of mean data curves for intersegmental angular velocity (right) from marker-based calculations and IMU measurements for cranial thoracic (CRT)–caudal thoracic (CDT) in the sagittal (upper row), dorsal (middle row), and transverse (lower row) planes.

comparison of 1 segment to the subsequent segment with a horse-based internal coordinate system. The data strings for each complete gait cycle were time normalized based on initial contact from the right forelimb IMU to the next initial contact. This rescales the time base from 0% to 100% of the gait cycle to allow direct comparisons between the marker model data and the IMUs.

Table 1—Intraclass correlations (ICCs) comparing intersegmental angular velocity data from marker-based calculations and inertial measurement unit (IMU) measurements.

	ICC	Lower bound ICC	Upper bound ICC	*P* value
Cranial to caudal thoracic				
Sagittal plane	0.985	0.984	0.986	< .001
Dorsal plane	0.854	0.844	0.863	< .001
Transverse plane	0.981	0.979	0.982	< .001
Caudal thoracic to lumbar				
Sagittal plane	0.987	0.986	0.988	< .001
Dorsal plane	0.964	0.962	0.966	< .001
Transverse plane	0.990	0.989	0.990	< .001
Lumbar to sacral				
Sagittal plane	0.991	0.99	0.991	< .001
Dorsal plane	0.875	0.867	0.883	< .001
Transverse plane	0.989	0.989	0.990	< .001

Statistical analysis

Intersegmental angular velocities in the sagittal, dorsal, and transverse planes were calculated using data from the markers and the IMUs. Shapiro-Wilk tests indicated that all data were normally distributed. The level of agreement between the 2 measurement techniques was determined using intraclass correlation coefficients (ICCs) and Bland-Altman analysis. Bias was assessed using the mean difference between the 2 methods of measurement for each paired data point, and 95% limits of agreement were reported as bias ± 1.96 X SD. Agreement between ICCs for the 2 methods was interpreted as follows: > 0.9, excellent; 0.75 to 0.90, good; 0.50 to 0.75, moderate; and < 0.50, poor.[18]

Results

Data were obtained from 4 sound horses, giving a total of 3,737 paired time points across 37 gait cycles, and agreement between the intersegmental angular velocities in each of the 3 planes of motion was explored using ICCs and Bland-Altman plots.

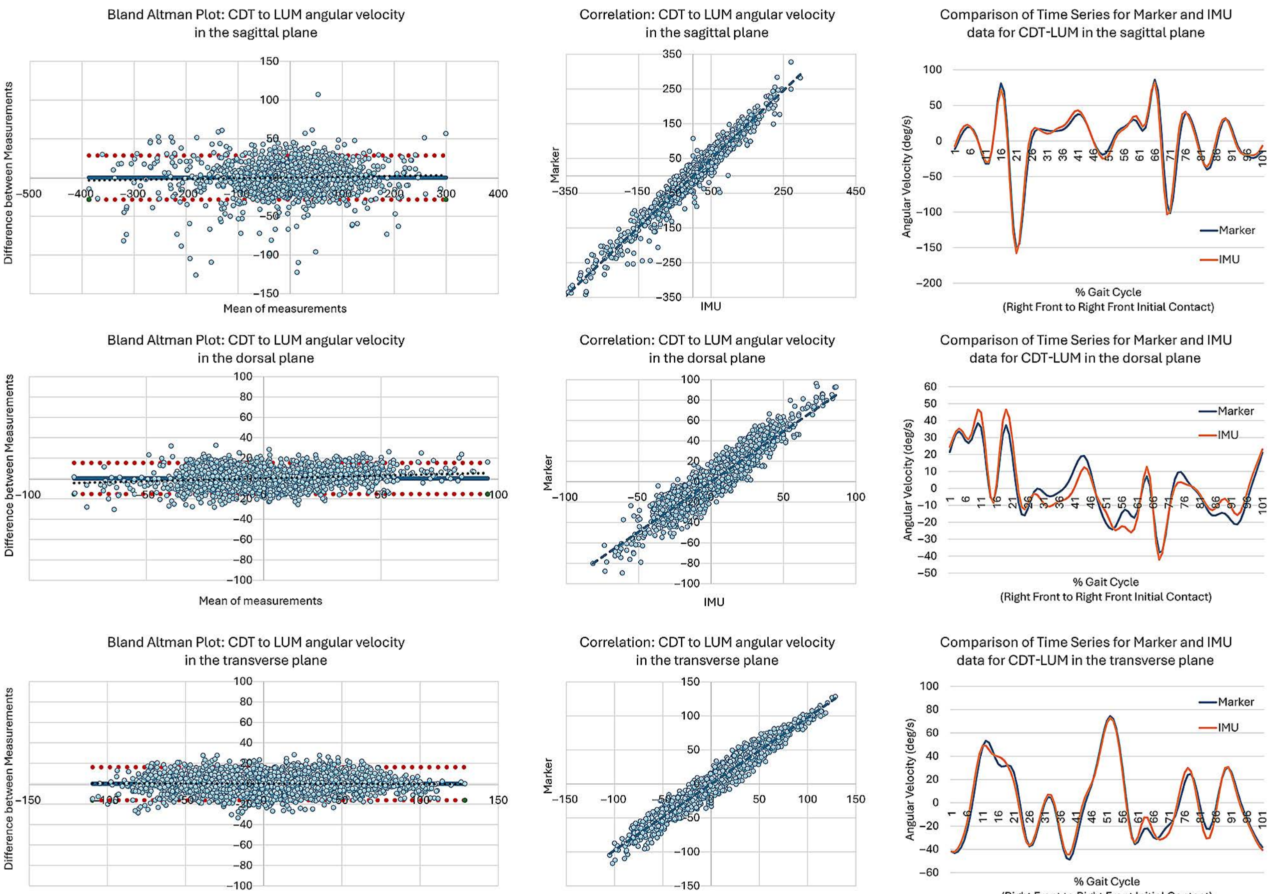

Figure 3—Bland-Altman plots (left), correlations (center), and comparison of mean data curves for intersegmental angular velocity (right) from marker-based calculations and IMU measurements for CDT-lumbar (LUM) in the sagittal (upper row), dorsal (middle row), and transverse (lower row) planes.

When using ICCs to compare intersegmental angular velocities between the CRT and CDT segments, agreement between the 2 methods was excellent in the sagittal and transverse planes ($r > 0.95$) and good in the dorsal plane ($r = 0.854$; **Figure 2**; **Table 1**). Comparisons between methods at the CDT to LUM segments showed excellent agreement in all planes ($r > 0.95$), with the sagittal and transverse planes exceeding $r = 0.98$ **(Figure 3)**. For the LUM to SAC segments, agreement in the sagittal and transverse planes was excellent ($r > 0.98$), and in the dorsal plane agreement was good ($r = 0.875$; **Figure 4**). The Bland-Altman plots, limits of agreement, and bias are presented in all figures and **Table 2**. The bias between the IMU and motion-capture data for all intersegmental planes of motion was not significant, indicating a negligible offset between methods. There were no notable trends between the mean and differences between measurements within the Bland-Altman plots, indicating no systematic disagreement between methods, although some disagreement can be seen at a few points within the movement curves, notably in the CRT-CDT and LUM-SAC dorsal plane results. When considering the marker and IMU data, 1-way ANOVA tests showed no significant main effects between horses. This indicates similar offsets and variation about the mean for angular velocity between the 2 methods for the different horses. Individual horse data is provided in **Supplementary Table S1**.

Table 2—Bias, limits of agreement (LOAs), and *t* tests (*P* values) comparing intersegmental angular velocity data from marker-based calculations and IMU measurements.

	Bias	*P* value	Lower 95% LOA	Upper 95% LOA
Cranial to caudal thoracic				
Sagittal plane	0.01	.987	−47.96	47.98
Dorsal plane	0.09	.804	−53.93	54.11
Transverse plane	0.00	.993	−36.83	36.83
Caudal thoracic to lumbar				
Sagittal plane	−0.02	.937	−28.45	28.41
Dorsal plane	0.03	.881	−15.27	15.32
Transverse plane	−0.01	.966	−16.18	16.16
Lumbar to sacral				
Sagittal plane	0.13	.512	−24.92	25.19
Dorsal plane	0.01	.986	−21.50	21.52
Transverse plane	0.09	.398	−17.48	17.65

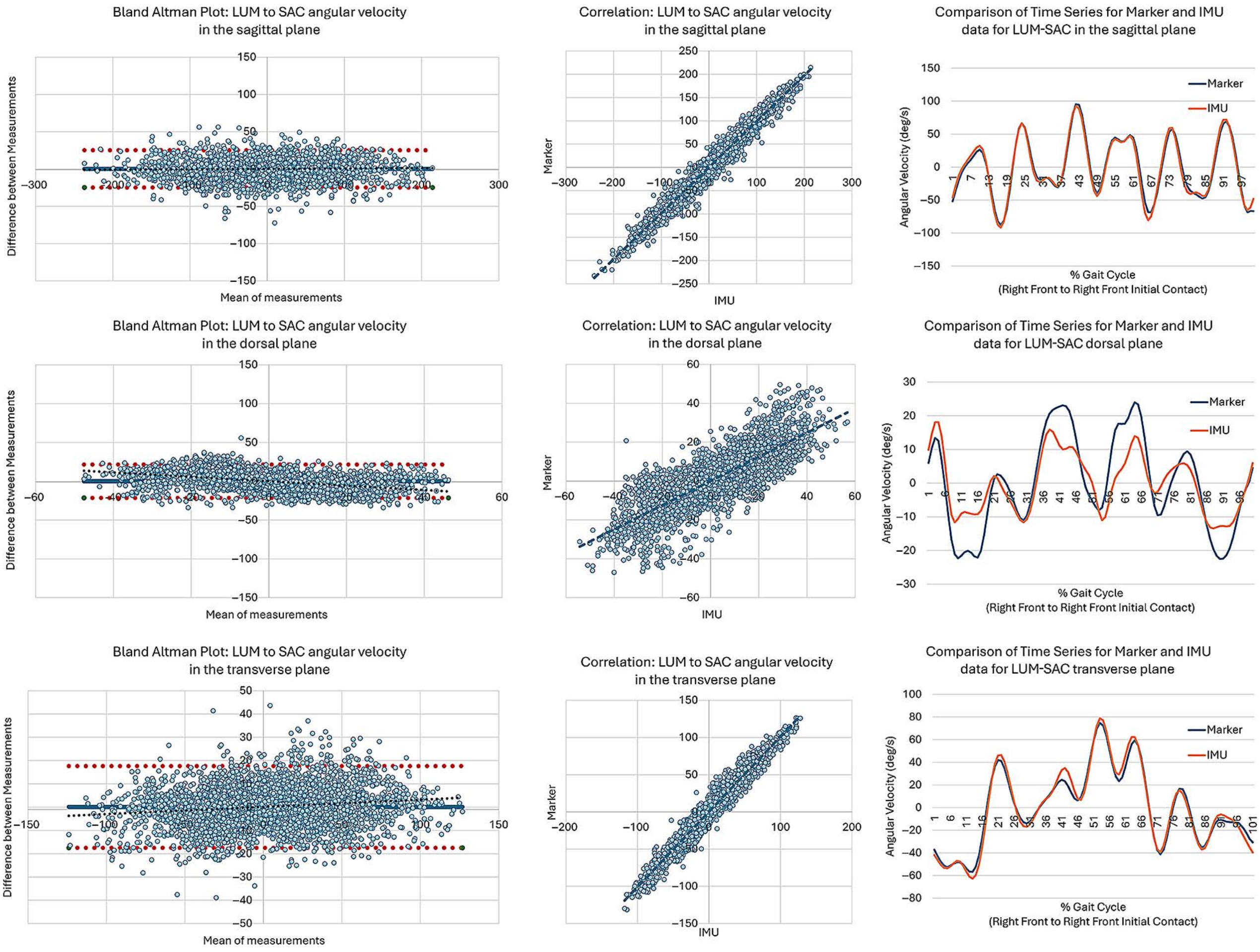

Figure 4—Bland-Altman plots (left), correlations (center), and comparison of mean data curves for intersegmental angular velocity (right) from marker-based calculations and IMU measurements for LUM-sacral (SAC) in the sagittal (upper row), dorsal (middle row), and transverse (lower row) planes.

Discussion

The purpose of this study was to determine if intersegmental angular velocity recorded from IMUs would be comparable to that calculated using the reference standard of camera-based motion capture. By demonstrating good to excellent agreement, the results validate the use of IMUs to assess topline motion in trotting horses. This opens up the opportunity to collect data outside of a laboratory setting under conditions that more directly reflect equine daily living and athletic activities in sport horses.

Excellent agreement was demonstrated between motion capture and IMU-measured angular velocity in all comparisons except the CRT-CDT and LUM-SAC junctions in the dorsal plane associated with lateral bending. One plausible explanation for this slight discrepancy may be associated with the orientation of the segment defined by the anatomical markers in relation to the cluster. The coordinate system for the motion-capture marker trials was based on the static standing trial. If a horse was not standing perfectly straight, the orientation may be slightly different from the IMU coordinate system. The dorsal plane would be most prone to a discrepancy during the static standing trial because lateral bending would be the most variable despite our efforts to maintain straightness and alignment. Another plausible cause relates to filtering. The 2 comparisons that show good agreement are also those with the lowest values and ranges of angular velocity. We elected to use a 15-Hz low-pass filter as most planes exhibited higher values of angular velocity. Therefore, the lower values may be slightly underfiltered and less smoothed, generating higher values in the marker data when compared to the IMUs. The use of a 15-Hz low-pass filter represents a balance between signal smoothing and preservation of true movement characteristics. Further exploration into specific processing techniques may be warranted; however, we feel that this conservative level of 15 Hz is a useful starting point, which is reflected by other work.[1,19]

When assessing spinal motion specifically, several human research groups have shown angular velocity to be more sensitive than angular displacements at identifying individuals with back pain[8] as well as assessing the quality of movement when patients perform a complicated task.[11] We showed similar differentiation potential when a lame horse was compared to sound horses, demonstrating a 184% difference between the 2 populations at the junction of the CDT and LUM segments in the sagittal plane.[1]

In humans, several comparisons to motion capture have been proposed in order to collect angular velocity measurements in patients without expensive and time-consuming motion-capture systems. Pomeroy et al[20] reported that the use of electrogoniometers was not a viable option; although there was a high ICC, the limits of agreement were also quite high. More recently, He at al[21] showed similar measurements for certain stride characteristics in normal patients at the walk, exhibiting ICC coefficients greater than 0.94 and $P < .01$. In comparison to the motion-capture system, the IMU showed excellent agreement for percentage of stance phase of stride, percentage of swing phase of stride, velocity in cm/s, and the step/min cadence.[21] Specifically regarding angles, Wirth et al[22] compared IMU measurements with motion capture of the wrist in 10 healthy individuals. It was determined there were no significant differences between the 2 methods for measurements of any of the movements recorded.

Inertial measurement units have previously been used to quantify motion in horses but only in terms of displacement data.[16,23–25] A gyroscope, which is a component of an IMU, measures angular velocity directly in the 3 planes of motion. This offers the possibility of a simpler method for determining intersegmental angular velocities, which have shown promise for objective assessment of quality of movement of the topline of the horse.[1]

Specific limitations of this study include the small number of horses used; however, the large number of paired observations were consistent between horses, which fulfilled the purpose of this study in comparing 2 methods of measurement rather than assessing changes within a population. Additionally, while the low-pass filter cutoff frequency was based on previous research,[1,19] this paper did not explore the optimal cutoff frequency for the IMU and marker-based data. However, further work to explore the optimum cutoff frequencies should be considered.

The results of this study showed minimal bias between measurements from marker data and IMU-derived measurements, with no evidence of systematic disagreement. In addition, the fact that agreement of the ICCs was excellent for 7 of the 9 comparisons and good for the other 2 and that the data showed such good agreement between the 3,737 paired time points supports the use of IMUs in the assessment of spinal intersegmental velocity. Collectively, these findings support the use of IMUs as a viable alternative to marker-based motion-capture systems for evaluating topline function in horses and facilitate broader clinical application in field settings.

Inertial measurement unit–derived measurements demonstrate strong agreement with motion capture for assessing intersegmental spinal angular velocity in horses. These findings support the use of IMUs as a practical tool for evaluating intersegmental motion of the spine in clinical non–laboratory-based settings. More research is required to determine the normal values of intersegmental angular velocity and how it changes in the face of clinical dysfunction or disease. However, these findings support the application of IMUs to assess intersegmental spinal angular velocity in non–laboratory-based conditions. Further applications may include serial assessments for rehabilitation monitoring, objective assessment in the response to treatment, and determining the influence of variables, such as different types of footing materials. With continued technological advancement, IMU-based angular velocity measurements may soon provide real-time insights into equine spinal kinematics and enhance rehabilitation and performance assessment.

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Disclosures

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Supplementary Materials

Supplementary materials are posted online at the journal website: avmajournals.avma.org.