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Original Research

Quantification of Equine Sacral and Iliac Motion During Application of Manual Forces and Comparison Between Motion Capture With Skin-Mounted and Bone-Fixated Sensors

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ABSTRACT

Diagnosis of sacroiliac dysfunction in horses includes manual motion palpation of the equine ilium and sacrum. Motion of the ilium and sacrum during manual force application to the equine pelvis has been measured previously in vitro. The aim of this study was to measure the amount and direction of motion in vivo, including comparison of bone-fixated and skin-mounted inertial sensors. Sensors were skin-mounted over tuber sacrale (TS) and third sacral spinous process of six Thoroughbred horses and later attached via Steinmann pins inserted into the same bony landmarks. Orientations of each TS and sacrum were recorded by one investigator during six trials of manual force applied to the pelvis, inducing cranial, caudal, and oblique rotations. Mean values were reported in Euler angles for the three orthogonal planes lateral bending, flexion–extension (FE), and axial rotation (AR). Differences between skin- and bone-fixated markers were determined with significance set at $P < .05$. The largest mean values recorded during rotations applied to the pelvises were for FE, (2.08° ± 0.35°) with bone-fixated sensors. AR gave the largest values recorded with skin mountings (1.70° ± 0.48°). There was a poor correlation between skin-mounted and bone-fixated markers with AR being the orthogonal plane in which results from skin mounting were closest to results from bone-fixated sensors Bony kinematics during external movement applied to the pelvis cannot be predicted from skin-mounted sensors, due to differences between skin- and bone-mounted sensors.

1. Introduction

In human physiotherapy, composites of motion palpation and provocation tests of the sacroiliac joint (SIJ) together have reliability sufficiently high for use in clinical assessment of sacroiliac dysfunction (SID) [1,2]. In horses, manual motion tests and provocation tests have been extrapolated from the human model. Establishing the nature and extent of equine SIJ motion is important to assist clinicians in determining if such tests are valid for the diagnosis of SID in horses.

Measurement of three-dimensional (3-D) movement at the SIJ presents a challenge in horses due to the location of the joint within the pelvis. Despite this, successful recordings of movements at both the sacral vertebral segment and the pelvis have been performed. Measurements of these two articulating segments of the SIJ allow an indication of motion that may occur at the SIJ. In vivo studies during treadmill locomotion have been performed in sound horses [3–10]. In vitro measurements limited to the sagittal plane revealed that less than 1° of movement existed at the SIJ, where the sacrum was moved against a fixed ilium [11]. Subsequent in vitro research using cadaveric equine specimens measured the amount of 3-D

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rotation occurring at the ilium with respect to a fixed sacrum. This was recorded with inertial sensors, during the application of movements based on manual motion tests that were applied to cadaveric pelvises [12]. Movement recorded in the sagittal rotation plane was only slightly greater than that recorded by Degueurce et al (2004) [11], but the range of motion of the ilium was greatest in the transverse or coronal plane, when lateral (2.56° ± 0.29°) and oblique (2.25° ± 0.29°) rotations were applied to the pelvis [12].

Relative movement between the ilium and the sacrum has also been noted as a change in cross-sectional area of the dorsal sacroiliac ligament (running from the tuber sacrale of the pelvis to the sacrum) occurring during application of manual forces to the pelvis in standing horses [12]. There has not, however, been a kinematic evaluation of the rotations that may occur during application of manual motion tests used in musculoskeletal examination of the SIJ in the horse to the pelvis in vivo.

The aim of this study was to measure the amount and direction of movement of the ilium relative to the sacrum in vivo, during the application of manual forces that are consistent with those used during a clinical physiotherapy examination of the equine pelvis. A further aim was to compare bone-fixated and skin-mounted inertial sensors.

2. Materials and Methods

2.1. Animals

Six thoroughbred horses were recruited, two geldings and four mares, mean age 7.6 years (range 4–14 years), mean weight 519.6 kg (range 480–553 kg), and mean height 159 cm (SD 3.2). The history of the horses was unavailable as horses were acquired from a sale yard. The horses were assessed by a veterinarian and a physiotherapist and judged to be sound.

2.2. Measurement and Sensors

Segment angles of both the sacral vertebral segment (S3) and the ilium (tuber sacrale [TS]) were recorded using three wireless inertial sensors numbered 1, 2, and 3 (Inertia Cube 3; InterSense, Bedford, MA www.intersense.com/InertiaCube_Sensors.aspx). The Inertia Cube 3 (IC3) sensors measure absolute orientation of any object relative to gravity and magnetic north. The collection frequency for the sensors was 100 Hz. Previous work has shown that the sensors have a static accuracy of better than 0.05° when appropriately configured [13].

The IC3 sensors contain an accelerometer, a magnetometer, and a gyroscope in each orthogonal plane. The orthogonal planes referred to are those denoted by the standard right-handed orthogonal Cartesian coordinate system. Flexion–extension (FE) is described as rotation around the x-axis; lateral bending (LB) is described as rotation around the z-axis; axial rotation (AR) is described as rotation around the y-axis. Orientation in this study was reported as Euler angles. All data were collected and analyzed using LabVIEW 7.1 (National Instruments, Austin, TX).

2.3. Skin-Mounted Sensors

Xylazine 150 mg was administered intravenously to each horse, before the horse being clipped over the regions of the TS, sacral dorsal spinous processes (SP), and caudal lumbar SP, to ensure an adequate area for adhesion of sensors and their batteries. Adhesive stretch tape (Fixomull) was applied over the bony prominences of both TS and the SP of S3, and an ink marker denoted the midpoint of each bony prominence (in the horse standing squarely). IC3 sensors were placed over the ink mark on the bony prominences, fastened with double-sided tape, and further fastened down with adhesive stretch tape.

Sensor 1 was attached onto the left TS; sensor 2 was attached onto the right TS; and sensor 3 was attached onto the sacral vertebral segment, for each horse. Horses were placed in stocks and were encouraged to stand squarely at all times during the testing. For applications of manual forces to the left side of the pelvis, only data from sensors 1 and 3 were recorded. Orientations of the left ilium and the sacrum were simultaneously recorded by the two sensors in three orthogonal planes, LB, FE, and AR, during rotational manual forces applied to the left pelvis by a physiotherapist (L.M.G.). The movements were assessed to the end of available passive range, reported as firm resistance to the induced motion [14,15]. The manual forces were applied in the following directions:

1. Cranial pelvic rotation (sagittal plane).
2. Caudal pelvic rotation (sagittal plane).
3. Oblique rotation (transverse-frontal plane).

The induced motions were applied via the therapist's hands placed over the ipsilateral tuber coxa and the tuber ischium for cranial and caudal rotations and the ipsilateral tuber coxa and contralateral tuber ischium for oblique rotation.

Before data collection, at least one test application of each rotation was applied to the pelvis, on each side. During manual force application, if the horse moved from the square standing position or there was muscle contraction, the application of rotation to the pelvis was repeated. There were three trials recorded for each application. For applications of manual forces to the right side of the pelvis, data from sensors 2 and 3 were recorded.

Data were sampled at 20 samples per second. Data was collected using a custom analysis program (LabVIEW 7.1), where they were represented as graphs. The difference between maximum and minimum values on the graph was calculated for each sensor and recorded as the Euler angle for each orthogonal plane.

2.4. Bone-Implanted Sensors

Bone implantation was carried out following the testing of the horses with skin-mounted inertial sensors without randomization of order due the possibility of bone implantation affecting the overlying skin. Horses were sedated with xylazine 200 mg and butorphanol 20 mg IV. Before pin insertion, gentamicin (6.6 mg/kg) and 2 g phenylbutazone were administered IV. A 4- to 8-cm-long, 3.0-mm-thick Steinmann pin was placed into the SPs (last lumbar and S2 or 3) and both TS without predrilling and was cut so that each pin protruded approximately 1 cm above the skin. Custom-built light-weight brackets, weighing 9 g and measuring 34 × 25 × 20 mm (Fig. 1) with an IC3 sensor screwed to the same, were fixed, via two tightening nuts, to the protruding end of each Steinmann pin on the left and right TS, the S3 SP in the same configuration for the skin-mounted situation. There was a fourth sensor pinned into the last lumbar vertebral SP. Sensor 1 was pinned into the left TS; sensor 2 was pinned into the right TS; and sensor 3 was pinned into the SP of the sacral segment.

The procedure of testing was identical to that of the skin-mounted inertial sensors. Orientation of the left and right ilium and the sacrum was simultaneously recorded by the sensors in three orthogonal planes. Data were collected and recorded in the same manner as for the skin-mounted sensors.

2.5. Statistical Analysis

For each direction of applied rotation, the degree of motion of LB, FE, and AR was recorded at each sensor. The results were

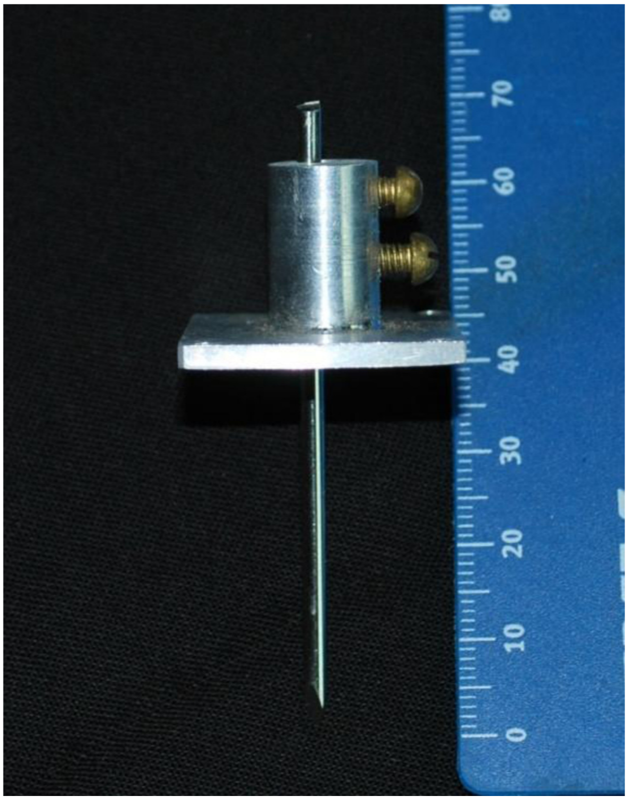

Fig. 1. The custom-built light-weight aluminum bracket for mounting of inertial sensor.

averaged over the six horses and presented as mean angle ± standard error of mean. Data were tested for normality, and paired *t*-tests were used (STATA, Version 10) to ascertain if there were significant differences between results obtained from bone-fixated sensors, from those obtained with skin-fixated sensors, for each direction of movement. Data were then analyzed using general linear model processing in SAS fitting terms for subject and sensor. Least squares mean was estimated for the aforementioned effects and compared using post-hoc t-tests. Spearman's correlation coefficient was calculated to determine if there was any predictable relationship between skin- and bone-mounted values.

3. Results

3.1. Skin Versus Bone Markers

Table 1 lists the means ± SD for all horses, recorded in Euler angles, for each orthogonal plane, during each application of rotation.

3.1.1. Skin-Mounted Data

Across all measured angles, the largest range of motion was recorded for AR during application of right oblique rotation to the pelvis, measured on the right TS (1.70° ± 0.2°) (Fig. 4). The smallest movement was 0.51° ± 0.11° recorded at the left TS during application of left oblique rotation for FE (Fig. 3). The general range of sagittal plane motion (FE) during induced movement was 0.5°–1.5°; the range of LB was 0.7°–1.3°, and the general range of AR was 0.6°–1.7°.

3.1.2. Bone-Fixated Data

Across all measured angles, the largest movement recorded was FE, during application of left oblique rotation, measured on the right TS (2.08° ± 0.15°) (Fig. 3). AR gave the smallest range of motion during application of right caudal rotation, at the right TS, (0.42° ± 0.08°), the sacral segment (0.46° ± 0.07°), and the left TS (0.46° ± 0.08°) (Fig. 4). The general range of sagittal plane motion (FE) during induced movement was 1.1°–2°; the range of LB was 0.5°–1.2°; and the general range of AR was 0.4°–1.4°.

It can be seen in Fig. 3 that in all instances, the values using bone-mounted sensors are greater than those for skin-mounted in this plane. FE was significantly different between skin- (0.59° ± 0.27°) and bone-mounted (1.59° ± 0.10°) sensors on the left TS ($P < .05$) and between skin- (0.61° ± 0.12°) and bone-mounted sensors (1.67° ± 0.14°) on the right TS ($P < .01$), during

Table 1
Range of motion at each of three sensors (means ± SEM, n = 6 horses), recorded in Euler angles, for each orthogonal plane, during the application of manual rotational forces (caudal, cranial, and oblique) on either the left or right side of pelvis.

Rotation	Mount	Plane	Left Pelvic Movement			Right Pelvic Movement		
			1	2	3	1	2	3
Caudal	Skin	LB	1.19 ± 0.08		1.34 ± 0.30		1.05 ± 0.24	1.13 ± 0.19
		FE	0.95 ± 0.13		0.97 ± 0.09		0.96 ± 0.12	1.00 ± 0.08
		AR	1.19 ± 0.53		1.12 ± 0.53		0.82 ± 0.24	0.67 ± 0.28
	Pin	LB	0.57 ± 0.11*	0.62 ± 0.11	0.75 ± 0.10	0.88 ± 0.07	0.92 ± 0.14	1.02 ± 0.12
		FE	1.18 ± 0.14	1.15 ± 0.26	1.16 ± 0.15	1.60 ± 0.46	1.55 ± 0.46	1.47 ± 0.41
		AR	0.90 ± 0.22	0.78 ± 0.20	0.89 ± 0.28	0.46 ± 0.08	0.42 ± 0.08	0.46 ± 0.07
Cranial	Skin	LB	0.73 ± 0.23		0.78 ± 0.16		0.87 ± 0.15	1.04 ± 0.24
		FE	0.59 ± 0.27		1.23 ± 0.21		0.61 ± 0.12	1.08 ± 0.27
		AR	1.20 ± 0.28		0.84 ± 0.16		1.29 ± 0.30	1.03 ± 0.27
	Pin	LB	0.86 ± 0.11	0.80 ± 0.15	0.99 ± 0.13	0.96 ± 0.14	0.73 ± 0.10	0.85 ± 0.15
		FE	1.59 ± 0.10*	1.80 ± 0.14	1.27 ± 0.04	1.53 ± 0.19	1.67 ± 0.14*	1.33 ± 0.18
		AR	0.79 ± 0.09	1.21 ± 0.20	0.76 ± 0.12	1.31 ± 0.19	1.23 ± 0.16	0.78 ± 0.10
Oblique	Skin	LB	0.73 ± 0.09		0.94 ± 0.20		0.95 ± 0.25	0.91 ± 0.17
		FE	0.51 ± 0.11		1.33 ± 0.21		0.86 ± 0.17	1.08 ± 0.23
		AR	1.16 ± 0.29		0.72 ± 0.20		1.70 ± 0.20	1.32 ± 0.31
	Pin	LB	0.66 ± 0.10	0.83 ± 0.07	0.78 ± 0.12	0.97 ± 0.19	0.95 ± 0.17	0.88 ± 0.17
		FE	1.96 ± 0.11*	2.08 ± 0.15	1.73 ± 0.16	2.07 ± 0.15	2.07 ± 0.18*	1.66 ± 0.19
		AR	1.17 ± 0.28	1.41 ± 0.27	1.00 ± 0.27	1.42 ± 0.25	1.32 ± 0.22	0.85 ± 0.20

Abbreviations: AR, axial rotation; FE, flexion extension; LB, lateral bend; SEM, standard error of mean.
Sensor 1 = left tuber sacrale; Sensor 2 = right tuber sacrale; Sensor 3 = sacral segment.
There were only two sensors recording at a time for skin-mounted data, the side of the application of rotation and the sacral segment.
* Significant differences between skin and pin mountings.

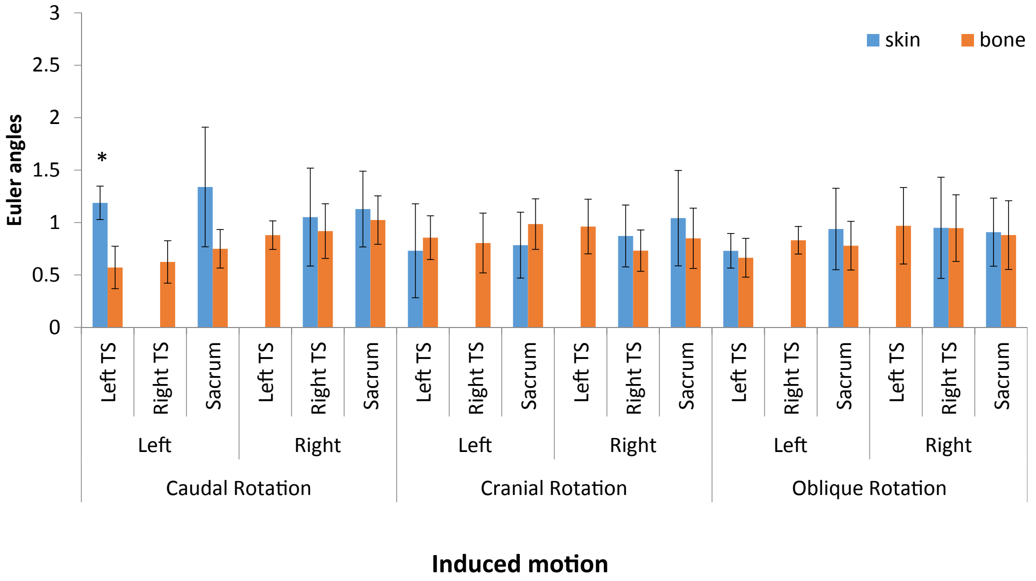

Fig. 2. Means of bone- and skin-mounted movements for lateral bending (LB). Error bars represent confidence interval of 95%. Asterisks represent significant differences between skin- and bone-mounted values. The relative movement is measured as Euler angles (y-axis). The induced movements are represented along the x-axis. TS, tuber sacrale.

application of right cranial rotation (Fig. 3). During left oblique rotation, FE was significantly different between skin- (0.51 ± 0.11) and bone-mounted sensors (1.96 ± 0.11) on the left TS ($P < .01$), and for right oblique rotation at the right TS (skin-mounted 0.86 ± 0.17; bone-mounted 2.07 ± 0.18) ($P < .01$), and a trend for difference on the sacrum (skin-mounted 1.08 ± 0.23; bone-mounted 1.68 ± 0.19) ($P = .068$) (Fig. 3).

From the graphs in Figs. 2–4, it can be seen that there were no consistent left–right differences in induced motion across all sites and angles. Sometimes, the amplitude of motion was greater on the contralateral side to where the movement was induced.

There was variable correlation between skin- and bone-mounted values, using Spearman's Correlation coefficient (Table 2). We can infer that there was a moderate to strong correlation between values from the two mountings for AR, moderate correlation for LB, and mostly weak correlation for FE.

3.2. Effect of Horse

3.2.1. Skin-Mounted Data

Post hoc analysis of analysis of variance of data derived from skin-mounted sensors showed that there was a significant effect of horse on the outcome for all orthogonal planes ($P < .05$). Least

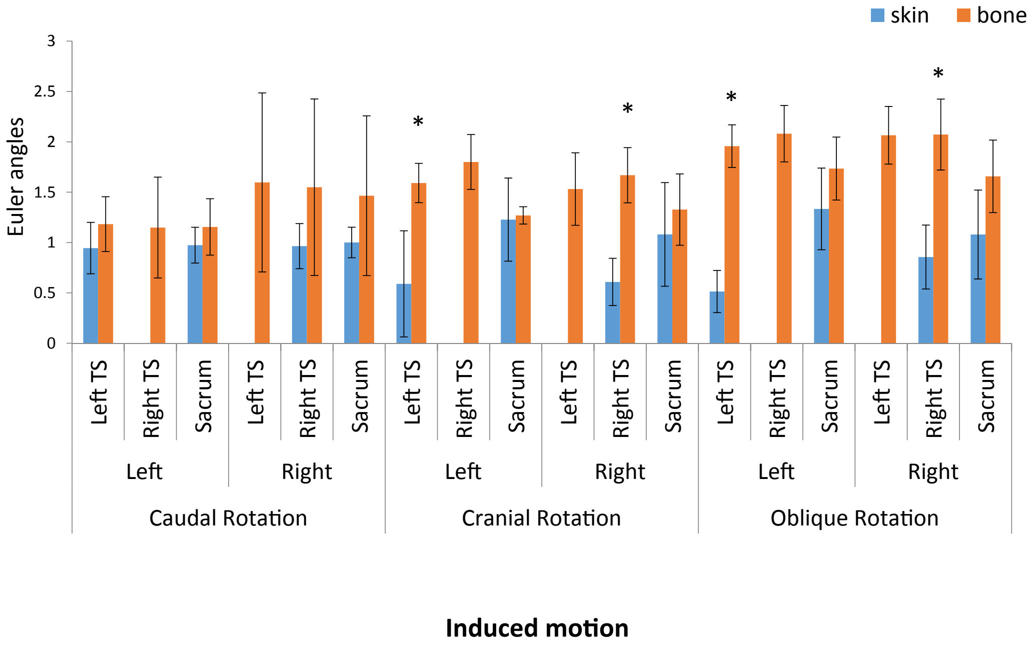

Fig. 3. Means of bone- and skin-mounted movements for flexion–extension (FE). Error bars represent confidence interval of 95%. Asterisks represent significant differences between skin- and bone-mounted values. The relative movement is measured as Euler angles (y-axis). The induced movements are represented along the x-axis. TS, tuber sacrale.

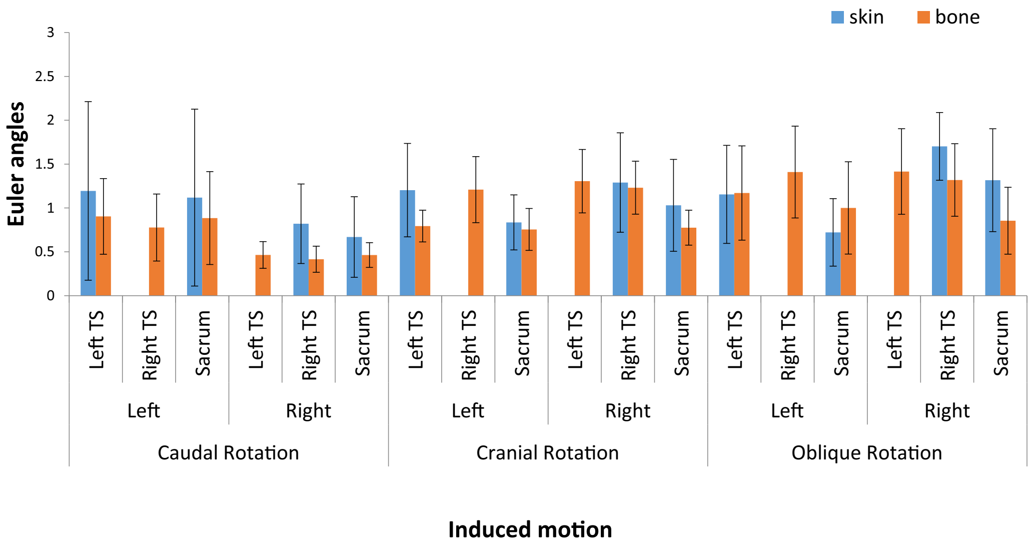

Fig. 4. Means of bone- and skin-mounted movements for axial rotation (AR). Error bars represent confidence interval of 95%. The relative movement is measured as Euler angles (y-axis). The induced movements are represented along the x-axis. TS, tuber sacrale.

squares mean values for all applications of rotation with skin-mounted sensors were greater for horses 6 and 1 when compared with all other horses. Table 3 shows the average range of motion for each horse. All means listed in the tables refer to least squares means.

3.2.2. Bone-Mounted Data

Post hoc analysis of analysis of variance of data derived from bone-mounted sensors showed that there was a significant effect of horse on the outcome for all orthogonal planes ($P < .05$). Least squares mean for motion during all applications of rotations with bone-mounted sensors in situ was greater for horse number 5 when compared with all other horses ($P < .05$). Table 4 shows the average range of motion for each horse.

When the mean values for each orthogonal plane for each horse from these tables were further averaged, values were similar between planes of motion for data derived from skin-mounted sensors. In data derived from bone-mounted sensors, FE was greater than LB and AR (Table 5) and indeed was greater during all induced motions in all situations.

4. Discussion

This is the first in vivo kinematic study to have measured the amount of motion that occurs at the equine ilium and sacrum during the application of manual forces, similar to those used in manual physiotherapy assessment of the equine pelvis and SIJ. This was achieved using orientation sensors mounted to both the skin and the relevant bony landmarks of the pelvis. This allowed differences in the Euler angles recorded from the two types of sensor mountings to be compared for this manual assessment procedure.

For the majority of the induced rotations applied to the pelvis by the physiotherapist, the mean values recorded in the orthogonal planes of LB and AR were greater for skin-mounted inertial sensors than mean values derived from sensors fixated into bone. Conversely, the values recorded in the sagittal plane of FE were greater from the bone-fixated sensors than the skin-mounted sensors, regardless of the motion induced. This may reflect the direction of movement or "sliding" of the pelvic bony prominences underneath the skin and fascia that occurs with rotations applied to the pelvis. That these differences were significant for the rotations in cranial and oblique directions could reflect that applications of these rotations (which require the therapist to deliver a ventrally directed force over the tuber coxa with one hand, and other hand using a more caudal force to assist the rotation from either the ipsilateral or contralateral tuber ischium) induces greater sagittal motion with pelvic bony movement, than caudally directed rotation.

In Fig. 3, the values of FE for the bone-mounted sensor over the sacrum appear to be smaller than values recorded over the tuber coxae and TS. Even though this pattern is not as clear for the orthogonal planes of LB and AR, the reason for less bone motion of the sacral segment under skin and fascia, compared with the TS,

Table 2
Spearman's correlation coefficient between skin- and pin-mounted data, during the application of manual rotational forces (caudal, cranial, and oblique) on either the left or right side of the pelvis in six horses.

Movement	Spearman's Correlation Coefficient		
	LB	FE	AR
Left caudal rotation	0.49	0.05	0.81
Right caudal rotation	0.60	0.95	0.12
Left cranial rotation	0.53	0.12	0.57
Right cranial rotation	0.40	0.15	0.36
Left oblique rotation	0.59	0.12	0.78
Right oblique rotation	0.16	0.43	0.70

Abbreviations: AR, axial rotation; FE, flexion-extension; LB, lateral bending.

Table 3
Mean range of motion in Euler angles in each orthogonal plane, for all applied rotations for each horse, using skin-mounted sensors.

Horse	LB		FE		AR	
	Mean Angle	SEM	Mean Angle	SEM	Mean Angle	SEM
1	1.2*	0.14	1.25*	0.13	1.09*	0.16
2	0.76	0.09	0.83	0.09	0.96	0.11
3	0.86	0.10	0.63	0.09	0.71	0.11
4	0.73	0.09	1.04	0.09	0.72	0.11
5	0.73	0.09	1.01	0.09	0.72	0.11
6	1.11*	0.10	1.10*	0.09	1.67*	0.11

Abbreviations: AR, axial rotation; FE, flexion–extension; LB, lateral bending; SEM, standard error of mean.

* When values were significantly greater than for other horses ($P < .05$).

Table 4
Mean range of motion in Euler angles in each orthogonal plane, for all applied rotations for each horse, using bone-mounted sensors.

Horse	LB		FE		AR	
	Mean Angle	SEM	Mean Angle	SEM	Mean Angle	SEM
1	0.70	0.06	1.57	0.10	0.95	0.07
2	0.89	0.06	1.47	0.10	1.33	0.07
3	0.84	0.06	1.68	0.10	0.79	0.07
4	0.76	0.06	1.60	0.10	0.89	0.07
5	1.05*	0.06	1.86*	0.10	1.08	0.07
6	0.78	0.06	1.45	0.10	0.68	0.07

Abbreviations: AR, axial rotation; FE, flexion–extension; LB, lateral bending; SEM, standard error of mean.

* When values were significantly greater than for other horses ($P < .05$).

could be due to the relative rigidity of the fascial and ligamentous attachments over the sacral SPs.

In some applications of rotations to the pelvis, the value recorded from the sensor on the ipsilateral TS was less than the sensor on the contralateral side. This is shown as an example in left caudal rotation and right cranial rotation in Fig. 2. The greater contralateral TS motion is most likely due to the pelvis moving as a 3-D structure. Even though there are left and right SIJs, each with a synovial component, reflecting the ability of each to move as an articulation, the pelvis is joined with the symphysis. Thus, movement applied to the left side of the pelvis will also be induced on the right side of the pelvis.

As has been noted in a previous study using both skin- and bone-mounted inertial sensors to investigate relative ilio-sacral motion [10], the correlation between measurements derived from the two different types of sensor mounting was poor. It is well established that the skin overlying a given bony prominence impedes direct observation and quantification of movement of that bony prominence [16,17] during gait. It is suggested that the discrepancy is due to both movement of the skin and preloading of the soft tissue under the sensor fixator [17]. This skin motion artifact, along with the previously discussed motion of the bones under the skin and fascia, is a likely reason for the poor correlation between measurements from the two sensor mountings in this study. Unlike in the gait-based studies, as the induced motions are applied to the horse in square standing, in this study, there would be very little effect from muscle contraction during the recording of the motion.

Despite there being poor correlation between recordings from the two types of sensor mounting, there may be able to be comparison of results within or between horses using skin-mounted sensors. Licka et al [3] noted, in a kinematic gait study of horses without back pain, that movement of the markers on the skin did not resemble motion of underlying bony segments. However, they concluded that skin-mounted markers could provide a method of comparison of horses with different gaits or movement patterns due to lameness [3]. Other authors have also concluded that skin-mounted markers could be used to evaluate the motion of the vertebral column in walking and trotting horses in a comparative way, where errors attributable to variability between strides and days are taken into account and correction for discrepancies occurs [8,16].

Table 5
Average of the mean ranges of the movements in Euler angles, for LB, FE, and AR, for all horses and all applications of rotation.

Mounting	LB	FE	AR
Skin	0.91	0.98	0.97
Pin	0.84	1.61	0.95

Abbreviations: AR, axial rotation; FE, flexion-extension; LB, lateral bending.

Owners of working or performance horses may not wish to have Steinmann pins fixated into the pelvis of their horse, whereas the idea of a noninvasive sensor attached to the skin may be less of a concern. Thus, despite poor prediction of skin-mounted data from bone-fixated data, as shown in this type of kinematic study, skin-mounted sensors may have a role in testing of kinematics of horses that are currently in work. Skin-mounted sensors may still provide clinically useful information about relative pelvic motion, as a baseline in working or performance horses, and following interventions or training program. In this study, the values from skin-mounted and bone-fixated markers diverge in the orthogonal plane of FE and a little in LB during motion applied to the pelvis, but there is very little difference for AR between skin- and bone-mounted values. We can see this from Table 5, where the average of all motions applied in all orthogonal planes is listed.

Clinicians may be able to compare values for rotations of bony segments of horses within groups, recorded from the skin overlying the bony segment, such as carried out by Pfau et al [18] in a comparison of lame versus sound horses with skin-mounted inertial sensors. This would be to ascertain if there were differences in patterns of motion between horses with SID and those that were sound, when orientation of bony segments of the pelvis were recorded from skin-mounted sensors during application of manual forces. We would be required to correct for error if trying to predict the kinematics of the underlying bony segment from skin-mounted sensors only. Motion sensors mounted to the skin could be used in evidence-based practice, to measure the result of a given manual therapy, training, or physiotherapeutic intervention. In this way, they are not measuring absolute motion of a segment, but simply given an objective measure before and after intervention.

An in vitro study of the application of similar rotations to the equine pelvis suggested that there may be therapist-based inconsistencies, in the induced rotation to the pelvis, which could be due to error in judgment of end of range of motion, or handedness of therapist [12]. The use of a pressure mat between the therapist's hand and the bony prominences of the pelvis may have helped to standardize the forces required to produce the rotations [12,15]. The increased FE (skin mounted) and LB (bone fixated) angles when movements were applied to the right versus the left pelvis imply that there was an effect of handedness measured in this study, although repeatability was good.

There were differences in the values obtained from the application of movements between horses. When skin-mounted data were recorded, horses 1 and 6 had significantly greater values than the other horses for motion recorded by the orientation sensors in all situation of induced motion to the pelvis. When bone-fixated data were recorded, horse 5 had significantly greater values than the other horses. Apart from the fact that these three horses were all the same height and aged 5 and 6 years, there does not seem to be a pattern as to the reason for the increased values. It would be a reasonable assumption that movement of bony segments would vary between horses, perhaps due to the horses' ages, level of ligament laxity, and orientation of the pelvis, or muscle development. Perhaps, some horses, such as horses 1 and 6, have greater mobility of skin over the bony landmarks or movement of the bony prominences under the fascia and skin. It is possible that horse 5 had relatively greater pelvic range of motion for the given applications of rotations to the pelvis—this could be due to relative pelvic ligament laxity or relatively reduced tone of the pelvic musculature. The fact that we see variations in the degrees of motion in a small sample size of same-breed horses highlights that clinically, orientation sensors may be best used within individuals for measuring baseline kinematics and then outcomes following interventions or training programs.

5. Conclusion

In this study, which examined the relative sacral and iliac motion of the equine pelvis during rotations applied by a physiotherapist using skin-mounted and bone-implanted orientation sensors, it was discovered that application of rotation to one side of the pelvis induces movement on the contralateral side. When assessing motion of the horse's pelvis in manual physical assessment, discrepancies between left and right oblique rotation may be the most readily detected by a clinician, due to the greatest overall motion being recorded via both mountings of sensors during this technique. When rotations are induced to the pelvis, motion of the bony prominences under the skin and fascia may be affected by the nature of the fascia and ligamentous attachments to the prominences. Due to the latter effect and the skin motion artifact, skin-mounted orientation sensors cannot be used to estimate kinematics of underlying bony segments movement in the horse, but as a noninvasive evaluation, they may be used as a comparative method of analyzing patterns of pelvic motion within individual horses. Skin-mounted orientation sensors may also be used as an outcome measure when looking at manual therapy interventions to the equine pelvis.

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References

[1] Arab A, Abdollahi I, Joghataei M, Golafshani Z, Kazemnejad A. Inter-and intra-examiner reliability of selected motion palpation and pain provocation tests for the sacroiliac joint. Man Ther 2009;14:213–21.

[2] Szadek KM, van der Wurff P, van Tulder MW, Zuurmond WW, Perez RS. Diagnostic validity of criteria for sacroiliac joint pain: a systematic review. J Pain 2009;10:354–68.

[3] Licka T, Peham C, Zohmann E. Range of movement at trot in horses without back pain. Equine Vet J Suppl 2001;33:150–3.

[4] Haussler K, Bertram J, Gellman K, Hermanson J. Segmental in vivo vertebral kinematics at the walk, trot and canter: a preliminary study. Equine Vet J Suppl 2001;33:160–4.

[5] Faber M, Schamhardt H, van Weeren R, Johnston C, Roepstorff L, Barneveld A. Basic three-dimensional kinematics of the vertebral column of horses walking on a treadmill. Am J Vet Res 2000;61:399–406.

[6] Faber M, Johnston C, Schamhardt H, van Weeren R, Roepstorff L, Barneveld A. Basic three-dimensional kinematics of the vertebral column of horses trotting on a treadmill. Am J Vet Res 2001;62:757–64.

[7] Faber M, Johnston C, Schamhardt H, van Weeren R, Roepstorff L, Barneveld A. Three-dimensional kinematics of the equine spine during canter. Equine Vet J Suppl 2001;33:145–9.

[8] Faber M, Schamhardt H, van Weeren R, Barneveld A. Methodology and validity of assessing kinematics of the thoracolumbar vertebral column in horses on the basis of skin-fixated markers. Am J Vet Res 2001;62:301–6.

[9] Gomez-Alvarez C, Rhodin M, Bobbert M, Meyer H, Weishaupt M, Johnston C, van Weeren P. The effect of head and neck position on the thoracolumbar kinematics in the unridden horse. Equine Vet J Suppl 2006;36:445–51.

[10] Goff L, van Weeren P, Jeffcott L, Condie P, McGowan C. Quantification of equine sacral and iliac motion during gait: a comparison between motion capture with skin-mounted and bone-fixated sensors. Equine Vet J Suppl 2010;38:468–74.

[11] Degueurce C, Chateau H, Denoix J-M. In vitro assessment of movements of the sacroiliac joint in the horse. Equine Vet J 2004;36:694–8.

[12] Goff L, Jasiewicz J, Jeffcott LB, Condie P, McGowan TM, McGowan CM. Movement between the equine ilium and sacrum: in vivo and in vitro studies. Equine Vet J Suppl 2006;37:457–61.

[13] Foxlin E, Harrington M, Altschuler Y. Helmet and head-mounted displays III, vol. 3362. Orlando, Florida: SPIE; 1998. p. 13–4. AeroSense 98.

[14] Maitland GD. Vertebral manipulation. 5th Edition. London: Elsevier Ltd.; 1986. p. 144–70.

[15] Haussler K, Hill A, Puttlitz C, McIlwraith C. Effects of vertebral manipulation on kinematics of the thoracolumbar region. Am J Vet Res 2007;68:508–16.

[16] Van den Bogert A, van Weeren P, Schamhardt H. Correction for skin displacement errors in movement analysis of the horse. J Biomech 1990;23:97–101.

[17] Taylor W, Ehrig R, Duda G, Schell H, Seebeck P, Heller M. On the influence of soft tissue coverage in the determination of bone kinematics using skin markers. J Orthop Res 2005;23:726–34.

[18] Pfau T, Robilliard J, Weller R, Jespers K, Eliashar E, Wilson A. Assessment of mild hindlimb lameness during over ground locomotion using linear discriminant analysis of inertial sensor data. Equine Vet J 2007;39:407–13.