Rider skill affects time and frequency domain postural variables when performing shoulder-in

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ABSTRACT

In equestrian sports the novice rider learns first to follow the movements of the horse's back and then how to influence the horse's performance. One of the rider's challenges is to overcome inherent horse/rider asymmetry patterns when riding in straight lines, mirroring the movements on the left and right sides when turning. This study compares the performance of novice and advanced riders when riding in sitting trot on straight lines and when riding shoulder-in to the left and right sides. Eight novice and eight advanced horse-rider combinations performed sitting trot in a straight line, shoulder-in left and shoulder-in right while wearing a full body set of inertial sensors. An experienced dressage judge indicated when the movements were being performed correctly and assigned scores on a scale of 0-10 for the quality of performance. Kinematic data from the inertial sensors were analysed in time and frequency domain. Comparisons were made between trotting on the straight, shoulder-in left and shoulder-in right. Advanced riders received higher dressage scores on all three movements, but significantly ($p<0.05$) lower scores were found for shoulder-in right across the two groups. When riding shoulder-in, advanced riders had greater hip extension (advanced=-5.8±17.7; novice=7.8±8.9 degrees) and external rotation (advanced=-32.4±15.5; novice=-10.8±13.2 degrees) in the outside leg compared with novices ($p<0.05$) and reflects an important cue in achieving the required body rotation in the horse. Lower scores for shoulder-in right may be linked to significant ($p<0.05$) changes in harmonics of trunk to pelvis rotation.

Key words: Horse riding, dressage, asymmetry, shoulder-in, posture, rider performance.

1.0 INTRODUCTION

Within the discipline of dressage, the rider's position and correct application of the cues applied by the legs, hands and seat aids are the basis for communicating with the horse to achieve and maintain optimal performance (Hobbs et al, 2020). The classical riding position for dressage dates to Xenophon 430-354 BC (Podhajsky, 1994), with modern literature stating that riders must maintain their seat over the horse's centre of gravity to develop and maintain horse-rider harmony (Mrozkowiak and Ambroży, 2014; Auty, 2007). In dressage, rider performance is largely determined by the ability to influence the horse's performance (Hobbs et al, 2020; Fédération Equestre Internationale (FEI) 2020) which is the focus of scoring criteria for a dressage test. Signals or ''aids'' from the rider pass information to the horse. An imbalanced riding posture can lead to incorrect application and/or timing of the hand, leg and/or seat aids, which confuses the horse (Podhajsky, 1994; McClean and McGreevy, 2010), and can, therefore, negatively impact horse-rider performance.

To date, rider and horse-rider performance in dressage has been studied mostly during sitting trot. Trot is a symmetrical gait, characterised by its two-beat, diagonally coordinated rhythm, which results in alternate support and suspension phases (Hobbs et al, 2016). When trotting in a straight line, rider symmetry is required to ensure minimal disruption to the horse and to provide optimal synchronicity (Byström et al, 2015; Engell et al, 2016). Rider skill is also differentiated in sitting trot by enhanced dynamic postural control of the trunk and pelvis during the large vertical and longitudinal variations in accelerations and decelerations of the horse (Byström et al, 2015). A recent scoping review (Hobbs et al, 2020) acknowledged the need for further investigation into rider skills, and their effects on performance in the horse, particularly during lateral movements. Shoulder-in is a lateral exercise that is considered valuable to trainers and riders, as it assists with suppleness, collection and straightness, thereby improving the horse's performance (Mendonça et al, 2020). It is also a required lateral movement in dressage tests of an intermediate or advanced level of difficulty. Shoulder-in is ridden in left and right directions and is often performed in sitting trot, and requires the rider to mirror the leg, hand and seat aids when performing to the left and right sides (see Figure 1). The aids for shoulder-in refer to the inside/outside hand and leg in accordance with the concave/convex sides of the horse. The rider's pelvis remains parallel with the horse's haunches while the rider's trunk, head and arms turn towards the inside, so the outside rein lies against the horse's neck. The rider's inside leg remains in position close to the girth and applies pressure. The combination of inside leg pressure and outside rein tension moves the horse sideways along the track. The rider's outside leg is retracted from the hip and lies against the horse's ribcage where it can apply pressure, if necessary, to prevent the haunches from swinging to the outside Kyrklund and Lemkow (1998).
During a dressage test, horse and rider performance are judged during the execution of movements in both directions (FEI, 2020), so horse and/or rider lateral preference and/or an asymmetric posture

may lead to different scores in the two directions. The effect of asymmetry on human performance has been investigated in other sports. For example, Li and Sanders (2005) have shown that symmetrical strokes improve efficiency and therefore enhance performance in swimming. A recent systematic review highlighted that asymmetry, across a range of physical qualities including inter-limb differences, may have detrimental effects on sports performance (Bishop et al, 2017). Research to date on rider symmetry within horse riding has found that anatomical and functional asymmetry may differ between rider ability/experience levels and that riding may exacerbate rather than improve asymmetry (Hobbs et al, 2014). During riding, greater right shoulder displacement associated with preferred left axial shoulder rotation was found by Symes and Ellis (2009) in all gaits except right canter. Evidence of laterality of both the horse and rider has been found within a right-handed population, where the rein tension of the rider was different between left and right sides, with less tension and range in the left rein (Kuhnke et al., 2010). Asymmetry in the rider may also influence movement symmetry in the horse (MacKechnie-Guire et al., 2020), but equally asymmetric sport horses are commonly found within the population (Greve and Dyson, 2014; Gunst et al., 2019). Asymmetry may become more pronounced with the increased complexity of the aids required to execute more advanced movements, like shoulder-in, which again may be detrimental for dressage performance. One study (De Cocq et al, 2010a) has investigated leg and saddle forces in dressage riders executing lateral movements. They found an increase in saddle and outside leg force when performing shoulder-in and travers compared to straight trot, but left and right directions were grouped in the analysis limiting their ability to investigate symmetry. As functional asymmetry is known to vary between and within riders when studying the time domain (for example see, Alexander et al., 2015), there may be advantages in studying asymmetry in the frequency domain. This type of analysis was proposed by Peham et al. (1996) for studying asymmetry due to lameness in horses, and further exploration of the harmonics of the frequency spectrum were used to investigate the smoothness of human walking by Menz et al. (2003).

Previous studies that have quantified rider posture and/or harmony have typically used inertial measurement unit (IMU) or motion capture technology to calculate phasic rider-horse movement (Münz et al, 2014; Baillet et al, 2017) or rider synchronicity specific to gaits (Peham et al, 2001; Wolframm et al, 2013; Byström et al, 2015). Motion capture studies have often utilised treadmill or mechanical horse methods (Byström et al, 2015) to collect multiple strides, however fewer have employed ridden tests during over ground locomotion; predominantly due to the camera configuration necessary to obtain a calibration volume large enough to capture multiple strides from a moving horse and rider. Studies investigating phasic relationships have successfully evidenced differences between novice and advanced levels of rider (Lagarde et al, 2005; Peham et al, 2001). Postural studies have identified more upright postures in advanced riders compared to novice or inexperienced riders, and differences in joint angles that relate to skilled rider characteristics (Schils et al, 1993; Lovett et al, 2005; Kang et al, 2010; Eckardt and Witte, 2017; 2016; Hobbs et al, 2020). Despite this, further research is required to quantify the impact of the rider on horse performance and dressage scores during over ground lateral movements.

The aims of this study were to compare rider posture in the time and frequency domain between i) straight-line trot and lateral (shoulder-in) movements, and ii) advanced and novice riders. It was hypothesized that significant differences in rider posture will be found between rider level (novice and advanced) and between shoulder-in (left and right).

2.0 METHODS

2.1 Participants and Horses

Ethical approval was obtained from the host university (MScSp&ExSci2011/JB). Prior to the study, riders were fully informed of the requirements, benefits, risks and procedures involved. Written informed consent was provided by all riders/horse owners prior to study inclusion. Riders completed a short questionnaire on their rider experience, previous injuries, handedness and information on their horse including level of training. None of the riders had been injured or were receiving treatment for injury in the year prior to collection. A total of 20 riders volunteered to participate and they were grouped into novice and advanced categories, based on their highest level of competition experience. Advanced riders were considered to be those who regularly perform shoulder-in in competition. Novice riders (n=10; Age: 28 ± 12 years; sex: male n=2, female n=8; Height:168 ± 7 cm; Mass: 65±10 kg) were competing at Open Novice to Elementary level (British Dressage Rider Groups 6-7) at the time of the study. Advanced level riders (n=10; Age: 29 ± 6 years; sex: female n=10, Height: 163 ± 7 cm; Mass: 67±6 kg) were competing in medium to advanced (British Dressage Rider Groups 2-5) at the time of the study.

The novice group rode one of three “schoolmaster” type horses (Age:17±2 years; Height:165±3cm Gender: mares n=2, gelding n=1; Breed: Thoroughbred n=1, Warmblood n=2), that were deemed sound by their owners. Horses were selected based on their previous level of training and competition experience (Elementary =1; Medium = 2). An experienced rider (British Horse Society Level 4 Coach, British Dressage Group 5 rider) trained these horses over a four-week period, prior to the commencement of the study. The advanced group rode their own competition horses, allowing varying levels of trained horses (Age = 12±2 years; Height = 167±5cm; Gender = mare x1, geldings x8, stallion x1; Breed = British Sports x1, Andalusian x1, Warmblood x7, Welsh Section D

Cross x1). All horses were ridden in their normal dressage saddle and bridle, equipped with a snaffle bit (Novice Group n = 10, Advanced Group n = 8), or double bridle (Advanced Group n = 2).

2.2 Equipment

An MVN Biomech full body IMU system from Xsens^{TM} (Netherlands) was used to measure three-dimensional movement from riders during the ridden test on the horse following previous published protocols (Munz et al, 2013). This system can be used in varying light conditions and allowed riders to mount and execute normal riding posture without interference from the sensors. The system includes a full-body suit, equipped with IMU sensors that provide six-degree-of-freedom tracking. Orientation and position of body segments were calculated by integration of the gyroscope and accelerometer data (Roetenberg et al., 2013). Data were recorded during the motion trials at 120 Hz. To mitigate integration drift, additional global positioning sensors (magnetometers) are incorporated into the sensor system, which, together with constant feedback from the kinematic model, update and correct the position and orientation of the segments on a frame-by-frame basis (Roetenberg et al., 2013).

2.3 Procedures

Riders wore normal riding breeches, boots and a tight-fitting top to ensure secure application of the sensors. A belt was used to hold the system battery packs in place and additional tape was placed around each sensor to limit displacement whilst mounting and riding. Anthropometric measurements were taken from anatomical landmarks and used to develop a model for each rider. A full calibration was performed prior to mounting the horse using the four poses suggested by the manufacturer; neutral pose (N pose), anatomical pose (T pose), squat and hand touch, which determine "sensor to segment" alignments based upon the methods described by Roetenberg et al. (2013).

Riders mounted the horses using a mounting block, taking care that sensors were kept in place. Prior to data collection, the riders were asked ride the horse in walk for 2-minutes to allow the calibration algorithm to accrue enough data to maintain the relative position of segments within the global coordinate system. Bent leg stirrup irons were used to avoid interference with the foot sensors. Riders were given 15 minutes to familiarise themselves with wearing the sensors and to warm up which included shoulder-in movements. Trials were then recorded during straight line trot (both reins) and shoulder-in movements in the left (left-rein on the inside) and right (right-rein on the inside) direction/reins. The first trial was always straight-line trot, but then subsequent trials were recorded in a random order. All trials were executed in sitting trot along the track and riders were asked to ride at a collected trot and to apply aids to the horse as they would normally when training or competing. Four trials of each condition were recorded whilst the movements were observed and scored by one dressage judge (BHS Stage 4 Senior Coach in Complete Horsemanship, UKCC Level 3, BD list 6 judge), in accordance with British Dressage (2020) and FEI (2020) dressage judging guidelines on a scale of 0-10 points. Each trial consisted of three strides, defined visually, using consecutive impacts of the horse's outside hind leg to define gait cycles. The use of coloured bandages aided visual identification of the stride pattern (see Figure 2). During shoulder-in, data acquisition began when the horse moved forwards on three tracks and the movement was deemed to achieve minimum judged score of 6, which is indicative that the performance is satisfactory. If a dressage score of 6 was not reached, the trial was discounted and repeated.

2.4 Data Analysis

Motion capture data from standing and dynamic trials were exported into Visual 3D software (C-Motion, USA) for analysis. The static (standing) trial was used to develop a model for each rider, which was applied to all dynamic trials for that participant. Dynamic trials were smoothed with a 4th order Butterworth low pass filter (Robertson and Dowling, 2003) with 6 Hz cut off frequency. Stride segmentation was conducted using maximum vertical displacement of the rider's head segment. This peak-to-peak event detection technique also served to convey the vertical displacement pattern of the horse's trot stride, as depicted by Bystrom et al, (2009) and De Cocq et al, (2010b). Some horse-rider combinations had missing trials due to data quality issues, so the number of trials for each condition varied between horse-rider combinations.

Two strides were extracted from each of the available trials for each movement. This provided between two and eight strides (most often four strides) of data for each horse-rider combination/movement for further analysis in the time domain. For frequency domain variables, the first stride from each trial was used in the analysis, so this provided between one and four strides of data (which was most often two strides).

Rotations between reconstructed segments were calculated from the dynamic data using an XYZ Cardan sequence, where X=flexion extension, Y=ab-adduction and Z=internal-external (axial) rotation. Time domain variables included mean right and left hip flexion-extension and mean internal-external rotation, trunk to pelvis flexion-extension ROM and mean axial rotation, mean difference between right and left anterior superior iliac spine (ASIS) vertical height (right minus left), mean difference between right and left acromion process vertical height (right minus left) and range of motion (ROM) for left and right knee flexion-extension. The sign conventions for mean posture variables were as follows:

- flexion and internal rotation positive.

- trunk to pelvis axial rotation - in the transverse view, right shoulder rotated towards the left side positive (counter-clockwise rotation when looking from above), left shoulder rotated towards the right side negative (clockwise rotation when looking from above).
- difference in height of ASIS and acromion process -higher on right positive, higher on left negative

For frequency domain variables, firstly the magnitude of 3D rotational motion of the trunk relative to the pelvis was calculated from the three rotational components (i.e. X,Y,Z). This variable was used in preference to each orthogonal component, as the frequency of overall 3D motion could be investigated. To calculate the magnitude, firstly, an arbitrary value of 100 degrees was added to all signal components to ensure that all values were positive. The square root of the sum of the squares was calculated and the waveform was centred around zero by subtracting its mean value over the stride cycles. This was calculated for each data point in the time series as shown in Eqn. 1

$$\theta_{3D} = \sqrt{\left((\theta_x + 100)^2 + \left(\theta_y + 100\right)^2 + (\theta_z + 100)^2\right)} - \overline{d\theta_{3D}}_{2\ strides} \text{ ....Eqn.1}$$

where θ_{3D} is 3D Trunk to Pelvis Rotation, θ_x , θ_y and θ_z are Trunk to Pelvis rotational components, and $\overline{d\theta_{3D}}_{2\ strides}$ is the mean value of θ_{3D} over two strides.

To compare the frequency content of 3D Trunk to Pelvis Rotation between riders, firstly the time of two strides for each trial was determined (range = 1.33-1.74 s). This was converted to a frequency (range = 0.574-0.750Hz) and used as the base frequency in the analysis which provided harmonics related to strides, steps, higher frequency components and inter-stride components. Discrete Fourier Transformation was then used to calculate the harmonic content of each 3D Trunk to Pelvis Rotation waveform for each stride individually.

The frequency domain analysis included an analysis of the power spectrum (see Figure 3). From each power spectrum mean frequency and total signal power were calculated. Mean frequency was the integral of the frequency-power curve (or area under the curve) divided by the total signal power. Total signal power was the sum of the amplitudes across the complete power spectrum. A higher mean frequency would indicate that higher frequency components within the signal had a higher amplitude and greater total signal power would suggest that the amplitudes of the frequency components overall were higher. For example, if there was a large amount of trunk pitch at the step frequency in one rider, due to being less stable (Byström et al, 2015) this would increase the mean frequency and total signal power compared to a rider with a stable trunk.

The harmonic content of the signal (see Figure 4) was explored further by examining the power content of the even (symmetric) harmonics compared to the odd (asymmetric) harmonics. The even harmonics are the sine components of the signal at each of the frequencies used in the analysis, the odd components are the cosine components of the signal at each of the frequencies used in the analysis. .One might expect that when riding sitting trot, 3D trunk to pelvis motion should contain symmetrical (sine wave) pelvis and trunk motion pitching motion per stride and asymmetrical (cosine wave) lateral flexion/axial rotation per stride to follow the motion of the horses' trunk (Byström et al 2009). An example from one trial of the harmonic waves from the stride and step frequency components plotted over time are shown in Figure 5. Other asymmetric harmonics might include altered rotation between one stride and the next that may be due to a loss of balance or limitations in following the motion of the horse. Harmonics at higher frequency may also be evident, particularly with increased stiffness in the rider (Alexander et al., 2015). For this analysis, firstly an overall harmonic ratio was calculated as the sum of squares of the even harmonics divided by the sum of squares of the odd harmonics (Menz et al., 2003), as shown in Eqn 2.

$$Harmonic\ Ratio_{stride} = \frac{\sum_{stride} Sin\ Harmonics^2}{\sum_{stride} Cosine\ Harmonics^2} \quad \text{............Eqn. 2}$$

As pelvic motion is primarily used in pitch and roll to damp the large accelerations and decelerations of the horse (Byström et al 2009), which has both symmetric and asymmetric components, it was anticipated that the harmonic ratio would be close to 1 in more skilled riders. Riders with greater symmetrical pelvic or trunk pitch might have a higher ratio than 1, whereas riders with inferior balance may have more asymmetrical harmonics and a ratio less than 1.To explore these data further, harmonic ratios of the square root of the sum of squares of all trials from each rider/at each frequency component were calculated up to the step frequency (see Equation 3) and then the sum of squares of spectral components from 3.195-7.029 Hz were calculated.

$$Harmonic\ Ratio_{frequency} = \frac{\sqrt{\sum_{trials} Sin\ Harmonics^2}}{\sqrt{\sum_{trials} Cosine\ Harmonics^2}} \quad \text{.............Eqn. 3}$$

The square root of the sum of squares was used to reduce the effect of over inflation of a ratio due to squared values increasing for harmonics over 1 and decreasing for harmonics below 1.

2.5 Statistical Analysis

Descriptive statistics were calculated for time and frequency domain variables and dressage scores (mean ± standard deviation and/or median, interquartile range) for straight trot. For shoulder-in left and right, the difference between shoulder-in and straight trot were calculated (shoulder-in minus straight trot) for the descriptive statistics. Dressage scores were retained as absolute values for shoulder-in. Data were grouped by side (left and right) and level (novice and advanced). A Shapiro-Wilk test confirmed normal distributions for each outcome measure. A repeated measures model was used to determine the effect of side within the riders, with rider level as a between-subjects factor to assess the interaction between side and level. Independent samples t-tests were used to compare between rider levels for straight trot and shoulder-in. Partial eta squared (η^2) values were calculated to estimate effect sizes for all significant main effects and interactions, and classified as small (0.01–0.059), moderate (0.06-0.137) or large (>0.138) (Cohen, 1988). Non-parametric data were compared using Wilcoxon Signed Rank Test (between left and right shoulder-in) and Mann Whitney U test (between rider level). Harmonic ratios of spectral components between novice and advanced riders and between straight trot and shoulder-in were explored post hoc using the same statistical methods. All statistical procedures were performed in SPSS version 26.0 (IBM SPSS, Chicago USA). Values of $p<0.05$ were considered significant.

3.0 RESULTS

Descriptive statistics for each outcome measure across rider level (novice and advanced) and movements (straight trot and left and right shoulder-in differences to straight trot) are presented in Tables 1 and 2. Two riders were removed from each group prior to data analysis, due to data quality issues, so the results are presented for eight riders in each group. All riders included in the study were right-handed. Non-parametric variables were; in straight trot all frequency domain variables except for higher frequency harmonic ratios, and for shoulder-in data dressage score, stride time and all frequency domain variables except for 3D Trunk to Pelvis Rotation signal power in shoulder-in left and higher frequency domain harmonic ratios in shoulder-in right. No significant main effects from the repeated measures model were found for level ($F(5)=1.099$, $p=0.488$, $\eta^2=0.687$), side ($F(5)=0.959$, $p=0.556$, $\eta^2=0.657$), or the interaction between side and level ($F(5)=2.253$, $p=0.191$, $\eta^2=0.818$) for the variables included in the model. Significant differences ($p<0.05$) were evident for key variables, as shown in Tables 1 and 2 and described below, and significant interactions ($p<0.05$) were evident for mean right and left hip flexion-extension and internal-external rotation.

3.1 Dressage scores

For straight trot significant differences were found between dressage score (see Table 1), with higher scores for the advanced group ($p<0.01$). Dressage score was also significantly higher ($p<0.05$) for the advanced group during shoulder-in movements and significantly higher scores ($p<0.01$) were found for shoulder-in left compared to shoulder-in right.

3.2 Time domain variables

A significantly ($p<0.05$) smaller trunk to pelvis flexion-extension ROM in shoulder-in left compared to straight trot is evident in the advanced group compared to the novice group (see Table 1). In addition, significant ($p<0.05$) time domain variables between groups and movements are found at the hip joint. In the advanced group in particular, hip mean flexion-extension are mirrored for left and right shoulder-in with greater extension compared to straight trot in the left hip for shoulder-in right and the right hip for shoulder-in left. For shoulder-in right, significantly ($p<0.05$) greater external rotation is found in the left hip and significantly ($p<0.05$) less external rotation in the right hip compared to straight trot in the advanced group. This is mirrored for shoulder-in left but was only significant for the right hip.

3.3 Frequency domain variables

For overall frequency domain variables, a significantly ($p<0.05$) higher 3D Trunk to Pelvis Rotation mean frequency was found for shoulder-in left compared to shoulder-in right with shoulder-in right much more similar to straight trot When comparing harmonic ratios for spectral components (see Table 3), a significant differences ($p<0.05$) between shoulder-in left and shoulder-in right were found at stride, inter-stride and step frequencies . For all three component groups a higher ratio was found for shoulder-in right, so the motion became more symmetrical. The power spectra are illustrated for straight trot and shoulder-in for both groups in Figure 3 and an example of the odd and even harmonics and 3D rotational motion of the trunk relative to the pelvis for a low scoring novice rider and a high scoring advanced rider are provided in Figure 4.

Table 1. Mean (standard deviation (s.d.)) for dressage scores (absolute), stride time (s) and time domain variables for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bold values are significant between rider levels. Shaded boxes are significant between shoulder-in left and shoulder-in right. Asterisks are where non-parametric statistical tests were used and median (inter quartile ranges) are also provided for non-parametric data. Number of trials for the group included in the analysis (n). For these variables (n) includes two strides. Anterior superior iliac spine (ASIS).

Kinematic Movement	**Magnitude**		**Difference between Shoulder-In and Straight Trot (except Dressage Score)**				
	Straight Trot		**Shoulder-in Left**		**Shoulder-in Right**		
	Nov mean (s.d.)	**Adv mean (s.d.)**	**Nov mean (s.d.)**	**Adv mean (s.d.)**	**Nov mean (s.d.)**	**Adv mean (s.d.)**	**p-value (Shoulder-In Left – Shoulder-in Right)**
	n=22	**n=18**	**n=17**	**n=13**	**n=18**	**n=17**	
Dressage score	**6.44 (0.15)**	**7.36 (0.69)**	**6.43 (0.16)**	**7.17 (0.66)**	**6.14 (0.15)**	**6.90 (0.84)**	0.002*
Median (inter quartile range)			**6.50 (0.25)**	**7.00 (0.38)**	**6.13 (0.25)**	**6.71 (6.71)**	
p-value (Nov-Adv)	**0.007**		**0.005***		**0.038***		
Stride Time (s)	0.78 (0.04)	0.79 (0.04)	-0.01 (0.04)	-0.02 (0.04)	-0.01 (0.03)	-0.001 (0.02)	0.289*
Median (inter quartile range)			-0.03 (0.03)	-0.01 (0.03)	0.00 (0.03)	0.00 (0.02)	
p-value (Nov-Adv)	0.577		0.878*		0.798*		
Trunk to pelvis flexion-extension ROM (deg)	19.9 (9.0)	21.6 (3.5)	**-1.9 (2.4)**	**-5.4 (3.3)**	-1.5 (5.3)	-3.9 (3.1)	0.197
p-value (Nov-Adv)	0.646		**0.032**		0.274		
Mean Trunk to Pelvis Axial Rotation (deg)	-4.0 (7.3)	0.64 (7.3)	-0.1 (4.6)	1.2 (9.0)	-3.6 (6.7)	-4.2 (8.8)	0.095
p-value (Nov-Adv)	0.225		0.726		0.877		
R-L Mean Difference in Acromion Process Height (mm)	0.4 (15.3)	0.9 (32.4)	0.6 (15.1)	-3.9 (16.8)	-1.5 (12.6)	7.7 (22.4)	0.379
p-value (Nov-Adv)	0.971		0.588		0.326		
R-L Mean Difference in ASIS Height (mm)	-2.6 (9.5)	-0.7 (19.7)	-2.6 (9.0)	4.7 (15.7)	16.5 (19.0)	2.7 (22.9)	0.132
p-value (Nov-Adv)	0.808		0.272		0.211		
Mean Left Hip Flexion-Extension (deg)	6.0 (10.1)	5.4 (12.7)	-1.0 (4.9)	1.0 (8.7)	**-0.3 (2.5)**	**-12.0 (7.0)**	0.041
p-value (Nov-Adv)	0.915		0.576		**0.001**		
Mean Right Hip Flexion-Extension (deg)	9.3 (6.5)	6.5 (10.9)	**0.8 (2.6)**	**-11.4 (10.7)**	-0.02 (5.2)	4.7 (6.1)	0.002
p-value (Nov-Adv)	0.538		**0.015**		0.121		
Mean Left Hip Internal-External Rotation (deg)	-18.6 (9.7)	-22.9 (12.7)	-0.6 (5.1)	9.4 (13.8)	**0.8 (5.7)**	**-11.6 (12.2)**	0.026
p-value (Nov-Adv)	0.459		0.087		**0.021**		
Mean Right Hip Internal-External Rotation (deg)	-8.8 (9.9)	-20.7 (16.5)	**5.3 (6.4)**	**-9.5 (17.1)**	**1.1 (5.7)**	**14.8 (6.4)**	0.009
p-value (Nov-Adv)	0.100		**0.047**		**<0.001**		

Left Knee Flexion-Extension ROM (deg)	8.4 (2.8)	7.9 (2.9)	<0.01 (1.5)	0.78 (3.1)	-0.2 (2.2)	-0.3 (1.1)	0.205
p-value (Nov-Adv)	0.729		0.536		0.874		
Right Knee Flexion-Extension ROM (deg)	9.4 (3.6)	6.9 (2.7)	0.2 (3.7)	-1.7 (1.8)	-0.3 (1.6)	0.4 (3.0)	0.329
p-value (Nov-Adv)	0.146		0.204		0.554		

Table 2. Median (inter quartile ranges) for frequency domain variables for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded values are significant between rider levels. Shaded boxes are significant between shoulder-in left and shoulder-in right. Asterisks are where non-parametric statistical tests were used. Number of trials for the group included in the analysis (n). For these variables (n) includes one stride.

Kinematic Movement	**Magnitude**		**Difference between Shoulder-In and Straight Trot (except Dressage Score)**				
	Straight Trot		**Shoulder-in Left**		**Shoulder-in Right**		
	Nov mean (s.d.)	**Adv mean (s.d.)**	**Nov mean (s.d.)**	**Adv mean (s.d.)**	**Nov mean (s.d.)**	**Adv mean (s.d.)**	**p-value (Shoulder-In Left – Shoulder-in Right)**
	n=22	**n=18**	**n=17**	**n=13**	**n=18**	**n=17**	
3D Trunk to Pelvis Rotation Mean Frequency (Hz)	3.12 (0.28)	3.16 (0.28)	0.35 (0.34)	0.05 (0.37)	0.07 (0.28)	0.01 (0.53)	0.049*
p-value (Nov-Adv)	0.721*		0.161*		0.505*		
3D Trunk to Pelvis Rotation Signal Power (deg^2*s)	51.5 (180.0)	93.3 (81.9)	-24.6 (49.6)	-49.3 (61.7)	-17.7 (76.2)	-33.5 (57.0)	0.215*
p-value (Nov-Adv)	1.000*		0.727		1.000*		
Harmonic Ratio	1.03 (0.10)	0.98 (0.09)	-0.02 (0.16)	0.04 (0.16)	-0.07 (0.20)	0.00 (0.16)	0.234*
p-value (Nov-Adv)	0.161*		0.234*		0.234*		

Table 3. Median (inter quartile ranges) for harmonic ratios for each spectral component for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded values are significant between rider levels. Asterisks are where non-parametric statistical tests were used. Number of trials for the group included in the analysis (n). For these variable (n)includes one stride.

Kinematic Movement	Magnitude		Difference between Shoulder-In and Straight Trot (except Dressage Score)				
	Straight Trot		Shoulder-in Left		Shoulder-in Right		
	Nov mean ± (s.d.)	Adv mean ± (s.d.)	Nov mean ± (s.d.)	Adv mean ± (s.d.)	Nov mean ± (s.d.)	Adv mean ± (s.d.)	p-value (Shoulder-In Left – Shoulder-in Right)
	n=22	n=18	n=17	n=13	n=18	n=17	
Two stride frequency	0.57 (0.83)	1.80 (1.63)	0.10 (0.70)	-0.59 (2.18)	0.96 (1.24)	1.73 (1.92)	0.098*
p-value (Nov-Adv)	0.161*		0.328*		0.442*		
Stride frequency	1.10 (1.48)	0.70 (2.01)	-0.26 (0.87)	0.56 (2.73)	1.29 (1.49)	2.73 (5.49)	0.034*
p-value (Nov-Adv)	0.234*		0.442*		0.442*		
Inter-stride frequency	0.87 (1.23)	0.71 (0.76)	-0.34 (0.92)	-0.11 (0.79)	1.38 (2.18)	0.94 (0.75)	0.030*
p-value (Nov-Adv)	0.645*		0.878*		0.798*		
Step frequency	1.12 (1.19)	1.89 (0.68)	0.12 (1.22)	0.76 (3.02)	0.93 (2.84)	0.42 (3.95)	0.469*
p-value (Nov-Adv)	0.195*		0.574*		0.645*		
Higher frequencies	0.95 (0.40)	0.79 (0.20)	0.05 (0.61)	0.03 (0.65)	1.09 (1.10)	0.97 (0.89)	0.007*
p-value (Nov-Adv)	0.468		0.878*		0.405		

4.0 DISCUSSION

This study used IMU technology to compare riders with different ability levels in terms of their dynamic posture in the time and frequency domain with the horse at sitting trot and shoulder-in. Not surprisingly, advanced riders received higher scores for all movements and showed better performance than novice riders with regard to several posture variables. These findings, together with a main effect of level support our first hypothesis. Significant differences were also found between shoulder-in left and right which supports our second hypothesis.

The fact that higher dressage scores were awarded to horses ridden by advanced riders is consistent with them having better posture and a higher skill level than novices, which facilitates better performance and higher scores.

The trot is an inherently symmetrical gait with the limbs moving in a diagonally synchronized pattern. The horse’s body undergoes a vertical excursion in each diagonal step (Buchner et al., 2000; Hobbs et al., 2013) and the rider is subjected to large accelerations due to the synchronized motion and force generation of the diagonal limb pairs (Clayton and Hobbs, 2017). Additionally, the horse’s trunk rotates around its centre of mass in a nose up direction in early diagonal stance, reversing to nose down rotation in late diagonal stance (Dunbar et al., 2008; Hobbs et al., 2013). Rotations of the rider's pelvis are the primary mechanism for the rider to absorb the horse's movements and communicate with the horse (Hobbs et al., 2020). The rider's pelvis pitches in the opposite direction and rolls in the same direction as the horse's back (Byström et al 2009).

The acetabulum of the hip joint is an integral part of the pelvis. When the rider's pelvis tilts anteriorly or posteriorly, it rocks onto the front or back, respectively, of the tubera ischii with the acetabulum rotating in the same direction. One of the skills acquired by the experienced rider is to be able to actively pitch the pelvis to follow the movement of the horse without changing the leg position. This implies that the rider allows the hip joints to flex and extend as necessary, so the position of the thigh is independent of pelvic pitching.

During shoulder-in, the rider positions the horse by turning the axis of the horse's shoulders to one side while the haunches remain straight. In this position, with the horse's shoulders at an angle to the line of motion, the inside forelimb crosses the outside forelimb each time it steps forward while the hind limbs continue to move straight along the original line. The riders inside leg acts in a forward position to maintain the bend in the horse's trunk, but the outside leg should move back along the horse's side and apply pressure to prevent the haunches from swinging outwards. The right leg should move back when performing left shoulder-in and the left leg should move back when performing right shoulder-in. Failure to move the outside leg back and use it to guard the haunches is a common rider mistake, especially in novice riders. The results presented here show symmetrical flexion-extension angles for the rider's left and right hips when riding on the straight as would be expected. In shoulder-in, the outside hip was significantly more extended (11.7^{o} in shoulder-in left, 13.2^{o} in shoulder-in right) in the advanced riders which has the effect of moving that leg back to control the haunches. The novice riders showed $\leq 1^{o}$ change in left or right hip angle when performing shoulder-in which likely represents the difference in level of skill with the novices failing to control the horse's haunches.

The rider's leg should be draped around the horse's trunk, which is somewhat oval in cross-section and widest around the height of the rider's knee. Since the rider's knee joints are mainly confined to rotate in flexion and extension, they cannot simply adduct their knee to wrap their calves around the horse. Therefore, in order to maintain contact with the saddle/horse with both the thigh and calf, the rider must either rotate the hip externally and/or flex the knee. We did not find differences in knee flexion between rider levels, whereas internal-external hip rotation values showed greater variability and were sometimes different between rider groups. This may indicate that hip rotation is used preferentially to adjust leg position and contact with the saddle. Furthermore, it has been stated that, in order to increase the horse's level of engagement whilst sitting in an upright dressage posture, riders must externally rotate their hips and, by doing so, they are able to absorb greater vertical movement of the horse's centre of mass and apply more consistent aids to the horse (Auty, 2007).

When riding in straight lines, left-right symmetry is highly valued, and riders strive to overcome their inherent sidedness patterns. The only positional variable that we observed to be asymmetrical when trotting on the straight was that the left hip was more externally rotated than the right hip in the novice riders, but this was not tested for significance. This observation agrees with Gandy et al. (2014) who used IMUs to evaluate 12 riders at rising trot on straight lies and circles. All riders showed asymmetrical external hip rotation with differences between left and right limbs in the range of 1-27^{o}, which is in the same range as we report here. Furthermore, 83% of riders showed greater external rotation of the right hip regardless of the direction of motion or which diagonal they were rising on. In a study comparing ballet dancers with non-dancers, strength, work, and angle specific torque of the hip external rotator muscles were reported to be greater on the right side than the left ($p = 0.007$) in both groups (Gupta et al., 2004). Thus, differences in hip rotation between the left and right legs may be a manifestation of inherent sidedness patterns. When performing shoulder-in, the advanced riders had greater outside hip external rotation and a reduction in external rotation of the inside hip. This would have the effect of turning the toe outwards in the outside leg and slightly more inwards in the inside leg which is in accordance with their functions of guarding the haunches vs bending the horse. Novice riders did not have a consistent pattern.

The equestrian literature emphasizes the importance of the rider's seat as the foundation for good performance, where the seat can be defined by hip and pelvis posture and motion, and lumbar spine mobility (Schusdziarra and Schusdziarra, 1993). Several scientific studies have confirmed that the phase synchrony between movements of the rider's pelvis with those of the horse is a key contributor to the impression of harmony (Eckardt and Witte, 2017; Lagarde et al., 2005; Münz et al., 2014; Peham et al., 2001). In this study we investigated 3D trunk to pelvis rotation harmonics to assess rider skill in the frequency domain, as no data were available from the horse. Together with a significant finding between shoulder-in left and right for mean frequency, there were interesting findings when exploring the spectral components. We predicted that harmonic ratios would be close to 1 in straight trot, due to the pitch, roll and yaw of the pelvis and trunk that occur within a stride (Byström et al, 2009; 2015). Indeed, this was the case in both groups, although from Figure 4 it is clear that the symmetric and asymmetric harmonics included in the ratio are not exclusively related to the stride and step frequencies. For shoulder-in left, a higher mean frequency is evident compared to straight trot, particularly in the novice group, but with lower signal power, whereas for shoulder-in right there is only a slight reduction in signal power. The changes for shoulder-in left may reflect the change in motion to give seat aids to the horse. When exploring the spectral components in more detail, harmonic ratios at the stride, inter-stride and step frequencies were higher for shoulder-in right, suggesting a more symmetric pattern. These alterations are also assumed to reflect the way riders give seat aids for shoulder-in right, but as they carry a lower dressage score could be considered less desirable. It could therefore be surmised that lower dressage scores for shoulder-in right in the advanced group relate to less desirable motion patterns that are produced as a result of seat aids, whereas lower dressage scores in the novice group are due to incorrect leg aids and undesirable motion to produce seat aids. A notable difference in magnitude and variability of the spectral components are illustrated between the rider groups in Figures 3 and 4, but unfortunately the relatively small group size and the variability, particularly in the novice riders, has limited our ability to analyse these data. Further work exploring the harmonics of both horse and rider motion, particularly at elite level, may prove fruitful in the development of determinants of dressage performance.

At the time these data were collected (year 2011) inertial sensor suits were not commonly used for biomechanical data collection from riders. A pilot study was therefore conducted to compare the inertial sensor data to data collected from a 3D motion capture system. The pilot test results found comparable ranges of motion between systems but highlighted how crucial sensor or tracking marker position on a segment are in extracting absolute angles (unpublished data). Such methodological issues have been reported in the literature (Leardini et al., 2005). Two additional methodological challenges are most evident when calculating axial rotation at the hip joint. Firstly, using an XYZ Cardan sequence, the Z axis is the third in the series of rotations to be extracted, introducing potential cross talk errors (Sinclair et al., 2012). Secondly, the model used in this study is based on rigid body mechanics, but the thigh segment, particularly the quadriceps muscles are quite deformable. As such, measured external rotation may include an artefact of a change in quadriceps position relative to the femur rather than modelled rotation of the femur at the hip joint. Due to these methodological limitations the analysis was focussed on comparisons between rider groups and movements, as any systematic errors are likely to be present throughout the dataset. Our scrutiny of the dataset also meant that riders and trials were missing from the analysis, which reduced the statistical power. Data quality issues were only evident during data processing, so collecting additional data was not possible for this study. The variability in the dataset may also be in part due to the difference between horses, tack and potential asymmetries within horses. Horses in this study were not screened to assess asymmetry prior to data collection. Finally, in this study multiple testing was not corrected for, based on the work of (Sinclair et al., 2013).

Despite the greater movement observed in advanced compared to novice riders, a key finding in the current study is the ability of the advanced riders to maintain and stabilise ‘ideal’ posture through their trunk and lower limbs, whilst absorbing motion through the pelvis and gaining higher dressage scores because of this. Future research should consider further investigation of other dressage movements and the balance between postural control and mobility in order to achieve greater performance outcomes in dressage tests across several levels.

5.0 CONCLUSION

This study has highlighted a difference in performance of the shoulder-in between advanced and novice riders in hip extension, and consequently the position of the outside leg to prevent the haunches swinging out. This is likely to have contributed to higher scores in the advanced riders. Since the difference was mirrored on the left and right sides, it is regarded as a voluntary part of the rider’s technique. Lower dressage scores for shoulder-in right are likely to be linked to changes in harmonics of 3D trunk to pelvis rotation due to the application of seat aids. Results from the current study have implications for equitation coaches and for horse and rider dressage performance.

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Author contribution

JB: Study design, data collection, data analysis, practical interpretation, manuscript preparation.
SJH: Study design, data collection, data analysis, statistical analysis, manuscript preparation.
JA: Data analysis, manuscript preparation.
LSG: Data analysis, manuscript preparation.
JS: Statistical analysis.
AC: Data collection, manuscript review.
HMC: Data analysis, practical interpretation, manuscript preparation.

Figure and Table Captions

Figure 1: Illustration of the correct position of the horse from above in straight trot and shoulder-in and an image showing one of the novice riders in the study performing shoulder-in left.

Figure 2: An advanced rider equipped with the XSENS suit and a corresponding reconstruction of the data for one trial for that rider.

Figure 3: Mean and standard deviation for novice A) and advanced B) riders of the 3D trunk to pelvis rotation power spectrum. Straight trot = dark blue, shoulder-in left = grey, shoulder-in right = cyan.

Figure 4: 3D trunk to pelvis rotation (degrees) and corresponding harmonics in straight trot and shoulder-in for A) and C) a low scoring novice rider, and B) and D) a high scoring advanced rider. Straight trot = dark blue, shoulder-in left = grey, shoulder-in right = cyan.

Figure 5: An example of the harmonics from a 3D trunk to pelvis rotation (degrees) from one trial at the A) stride frequency and B) step frequency.

Table 1. Mean (standard deviation (s.d.)) for dressage scores (absolute), stride time (s) and posture time domain variables for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded values are significant between rider levels. Shaded boxes are significant between shoulder-in left and shoulder-in right. Asterisks are where non-parametric statistical tests were used and median (inter-quartile ranges) are also provided for non-parametric data. Number of trials for the group included in the analysis (n), where each trial includes two strides. Anterior superior iliac spine (ASIS).

Table 2. Harmony Mean (standard deviation (s.d.)) for frequency domain variables for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded values are significant between rider levels. Shaded boxes are significant between shoulder-in left and shoulder-in right. Asterisks are where non-parametric statistical tests were used and median (inter-quartile ranges) are also provided for non-parametric data. Number of trials for the group included in the analysis (n), where each trial includes one stride.

Table 3. Mean (standard deviation (s.d.)) for harmonic ratios for each spectral component for straight trot and differences between shoulder-in and straight trot for left and right shoulder-in separated by rider level. Bolded values are significant between rider levels. Asterisks are where non-parametric statistical tests were used and median (inter-quartile ranges) are also provided for non-parametric data. Number of trials for the group included in the analysis (n), where each trial includes one stride.

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Figure 1

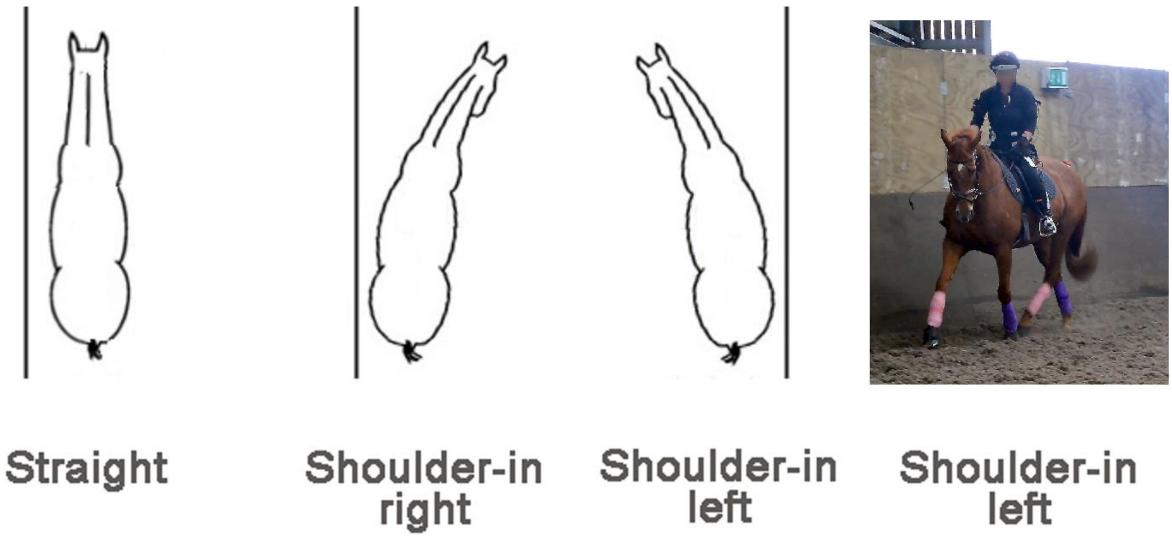


Figure 2

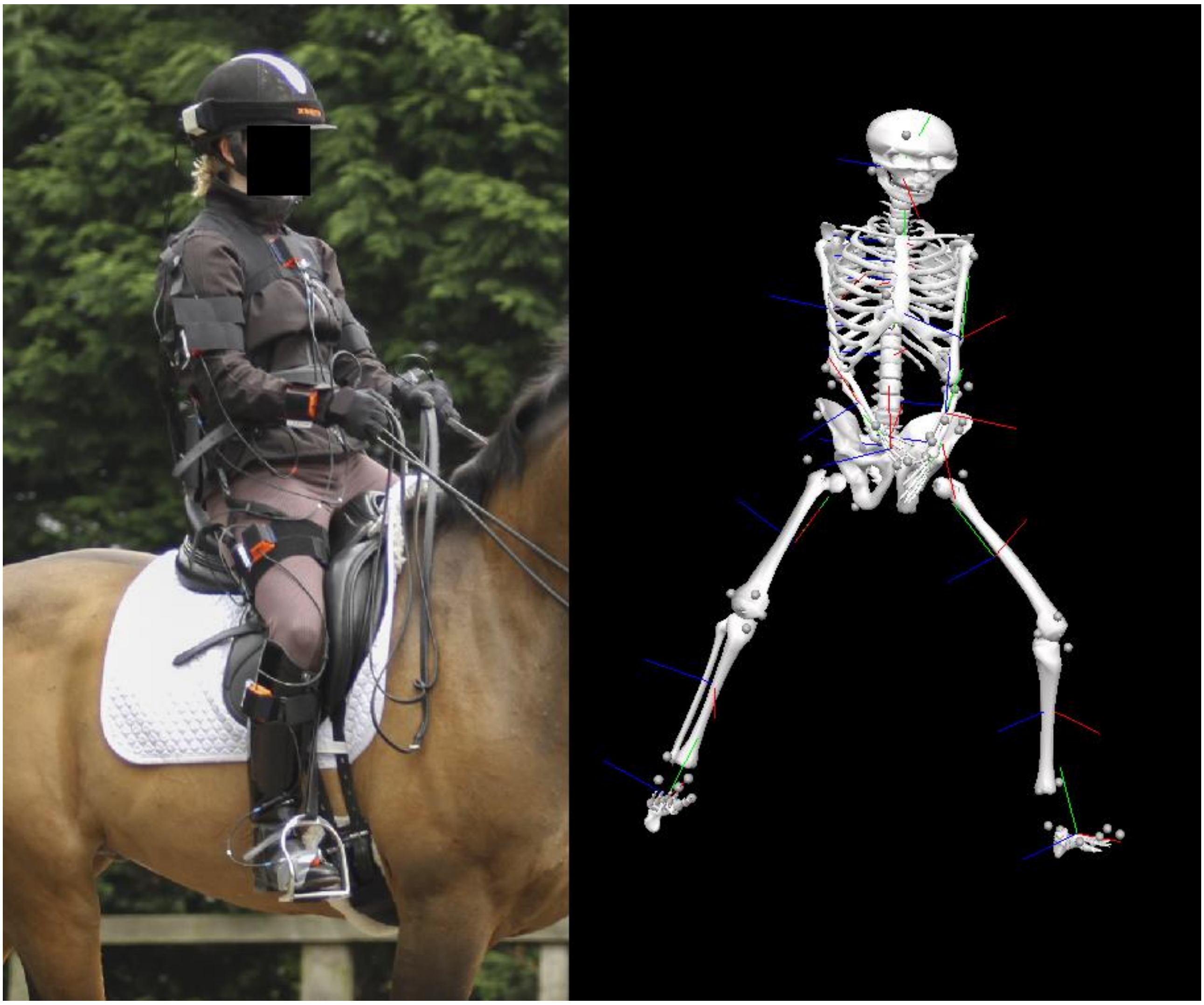
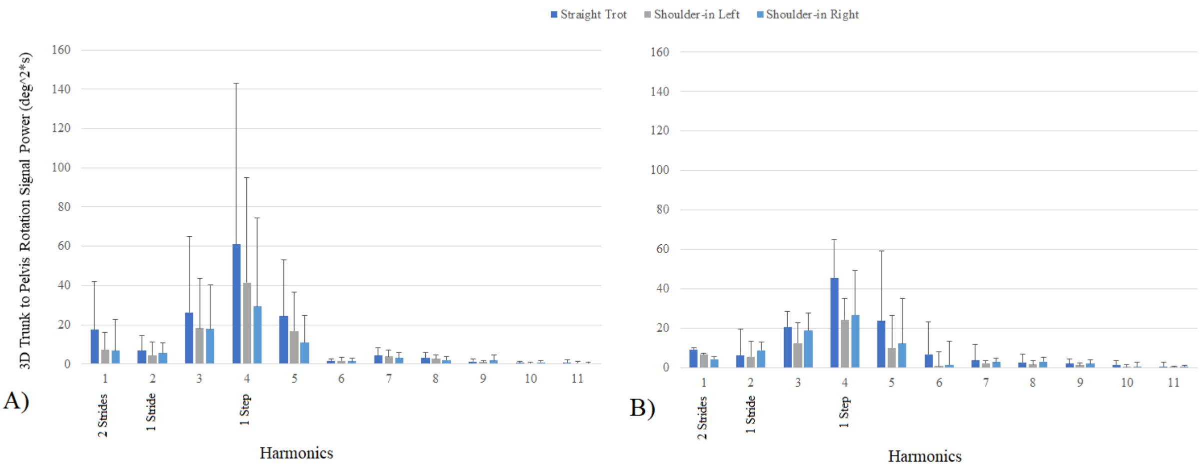


Figure 3



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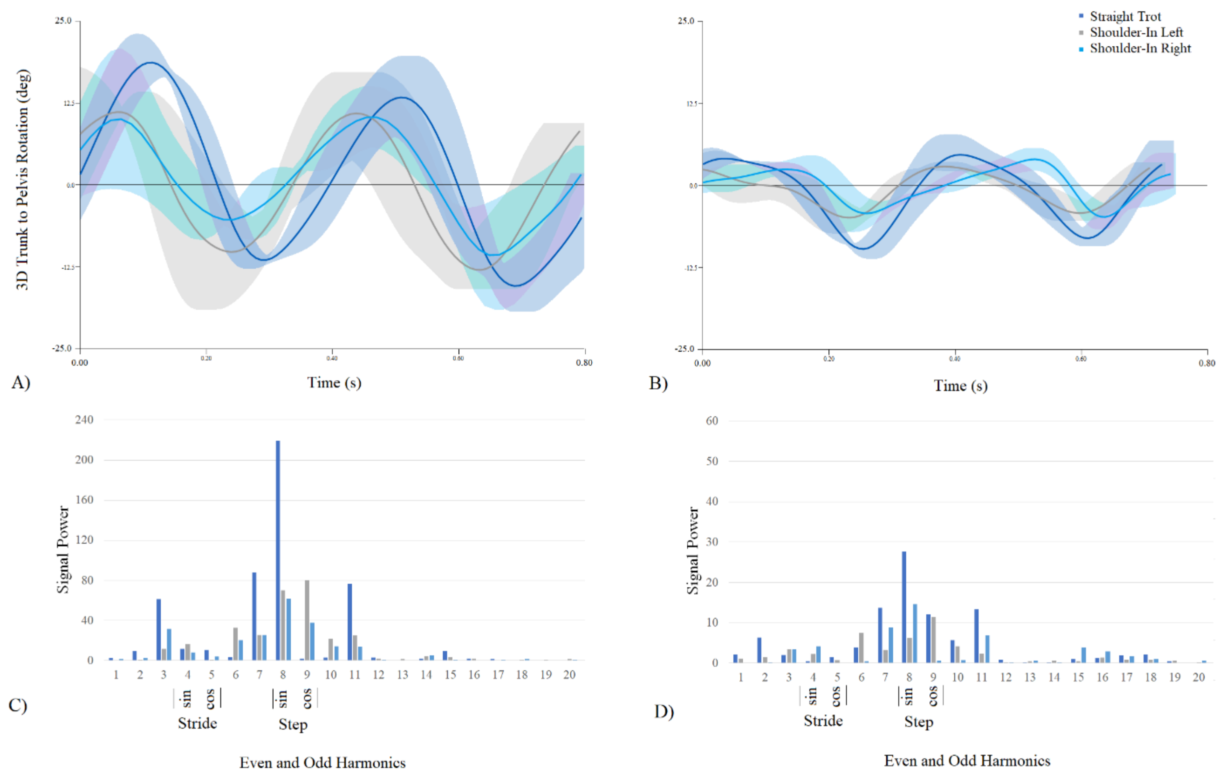

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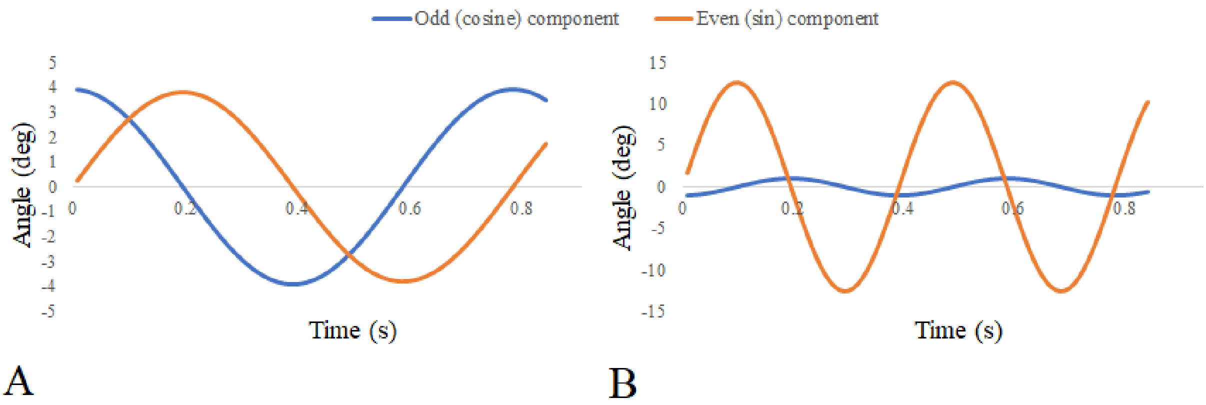

Odd (cosine) component
Even (sin) component
Angle (deg)
Time (s)
A
B