Static pelvic posture is not related to dynamic pelvic tilt or competition level in dressage riders

Celeste A. Wilkins[a], Kathryn Nankervis[a], Laurence Protheroe[a], Stephen B. Draper[a]

[a] Hartpury University, Hartpury, Gloucester, Gloucestershire, GL19 3BE. United Kingdom

Corresponding author: Celeste A. Wilkins celeste.wilkins@hartpury.ac.uk

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Static assessment and grouping of riders by competition level is prevalent in equestrian coaching practice and research. This study explored sagittal pelvic tilt in 35 competitive dressage riders to analyse the relationship between static and dynamic postures and assess the interaction of competition level. Riders were assessed using optical motion capture on a riding simulator at halt and in walk, trot, and left and right canter. Mean, minimum and maximum pelvic tilt, and range of motion (ROM) was measured as the pitch rotation of a rigid body formed by markers placed on the rider's left/right anterior and posterior superior iliac spines and sacrum, averaged over six time-normalised strides. Three key results emerged: (1) there are correlations between the rider's mean pelvic tilt in simulated walk, trot and canter, but not at halt; (2) mean pelvic tilt values are not significantly influenced by competition level ($p = 0.233$); and (3) the minimum and maximum pelvic tilt values illustrate individual strategies between gaits. Therefore, results from static assessment and grouping of riders by competition level should be interpreted with caution. Riders should be assessed as individuals, during dynamic riding-specific tasks, to understand their postural strategies.

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Introduction

The dressage rider's ability to achieve dynamic postural stability is integral to their performance and safety. Previous research and lay coaching texts propose several factors that may influence the horse-rider interaction, including rider competition level and experience (Baillet et al., 2017; German National Equestrian Federation, 2003; Lagarde, Peham, Licka, & Kelso, 2005; Münz, Eckardt, & Witte, 2014; Olivier, Faugloire, Lejeune, Biau, & Isableu, 2017; Peham, Licka, Kapaun, & Scheidl, 2001; Schöllhorn, Peham, Licka, & Scheidl, 2006). Studies have analysed the relevance of the rider's pelvic technique to the quality of the horse-rider interaction, with significant interactions between rider experience level and the kinematics of the pelvis found in some (Münz et al., 2014) but not all (Eckardt & Witte, 2017) studies. Indeed, biomechanical models proposed by de Cocq, Muller, Clayton, and van Leeuwen (2013) suggest that several combinations of trunk stiffness and damping result in in-phase coordination with the horse. A variety of pelvic and trunk postures have been observed in experienced, competitive dressage riders at halt and during sitting trot (Alexander et al., 2015) and during standing (Hobbs et al., 2014). The largest of these studies used 3D motion capture to measure posture and flexibility in 134 competitive dressage riders standing and seated in a static saddle (Hobbs et al., 2014). Their findings indicated that postural deviations from a neutral spine during standing, including lordosis, kyphosis, swayback and flatback, are common in riders, regardless of competition level or years of experience. As static postural assessment may reflect the individual's musculoskeletal balance and stability (Norris, 1995), it may provide a convenient tool to assess the rider. However, the relationship between static and dynamic postures in the rider is unclear. One known study to date has investigated this, observing strong significant correlations ($r = 0.83$, $p<0.05$ for left rein; $r = 0.88$, $p<0.05$ for right rein) between anterior-posterior pelvic tilt in halt and during the sit phase of rising trot in both directions for 16 experienced riders (Gandy, Bondi, Pigott, Smith, & McDonald, 2018). However, in rising trot, the rider actively rises out of the saddle on alternate diagonal stance phases, which places a greater demand on the legs, rather than the rider's lumbopelvic region, to determine the mechanical properties of the rider (de Cocq et al., 2013). Therefore, analysis of the relationship between seated postures at halt and seated postures in walk, trot and canter is justified.

The influence of the rider's pelvic tilt on their functional range of pelvic motion in seated walk, trot and canter is unknown. Furthermore, the evidence suggesting the effect of rider skill or competition level is equivocal. At the individual level, the rider's functional range of motion may factor into their incidence of back pain. If the rider adopts a large, uncontrolled anterior pelvic tilt throughout the stride, they risk increased shearing forces on the lumbopelvic region due to reliance on the passive stability afforded by elastic recoil of non-contractile tissues of the spine and facet joint approximation, rather than active stability by muscular contraction (Norris, 2008). Similarly, restrictions due to pain or abnormal myofascial length and recruitment limit the available range of pelvic motion (Comerford & Mottram, 2012). Hobbs et al., (2014) reported back pain in individuals with and without a neutral standing posture, which suggests the development of back pain in the rider is unrelated to their static posture and may relate to the demands of the sport. Indeed, the majority of individuals can intentionally adopt anterior, posterior or neutral pelvic positions when seated (Hayden, Hayes, Brechbuhler, Israel, & Place, 2018), however, their ability to maintain these postures during dynamic movements is unclear. Therefore, investigation of the relationship between the rider's static pelvic posture in the saddle and dynamic technique are warranted to inform specific interventions to enhance rider health and performance and performance.

As the relationship between the rider's halt posture, competition level and gait are unknown, the aims of this study were to use a riding simulator to; (1) explore whether patterns of pelvic tilt are related to rider competition level; (2) to examine whether there is an association between rider pelvic tilt in their static, seated position and during riding; (3) to describe the characteristics of the rider's range of pelvic pitching motion (ROM), including total mean ROM, minimum and maximum; (4) to compare mean pelvic tilt assessed in walk, sitting trot, left canter and right canter to determine whether riders follow a common pelvic technique. We hypothesise that riders will show common patterns of pelvic tilt, related to competition level.

Methods

Participants

Thirty-five adult female dressage riders participated in this study. The aim was to study competitive riders, therefore, riders were included if they had at least three results in British Dressage (BD) or competitions affiliated to the International Equestrian Federation (FEI). Riders were classed by their competition level based on the level of their three highest results in the last 6 months. Advanced level riders (n = 9, 3 professionals, mean age: 28.8 ± 11.5 years, height: 1.64 ± 0.1 m, mass: 66.1 ± 8.2 kg) were those competing in FEI classes (Grand Prix, Prix St George, Intermediare I or Intermediare II). Intermediate level riders (n = 15, 7 professionals, mean age: 31.9 ± 11.6 years, height: 1.56 ± 0.4 m, mass: 61.6 ± 8.6 kg) were competing at the upper levels of national competition (BD Medium, Advanced Medium or Advanced), and novice level riders (n = 11, 0 professionals, mean age: 27.8 ± 11.2 years, height: 1.63 ± 0.5 m, mass: 58.2 ± 7.6 kg) were competing at the introductory levels of national competition (BD Novice, Preliminary and Elementary). All participants were riding regularly at the time of the study, with no reported injury or pathology that stopped them from taking part in riding activities or competition. All participants signed informed consent and ethical approval was granted by the Hartpury University Research Ethics Committee.

Data acquisition

A riding simulator (Eventing Simulator, Racewood, Cheshire, UK) was used to collect the data as it allowed standardisation of the test and the ability to expose all riders to the same oscillations. Each gait produces specific amplitudes and frequencies of three-dimensional oscillations to simulate the movement of the horse's trunk in motion. The amplitudes of these oscillations and frequency by gait are listed in **Table 1**. Walk is the slowest gait, with the greatest mediolateral displacement. Trot features predominately dorsoventral displacement, and canter produces a large rocking motion that features the largest anterior-posterior displacement of all three gaits. Three markers were placed on the rear of the riding simulator to measure the anterior-posterior, mediolateral and dorsoventral displacements. There was a 41 mm difference in the minimum and maximum mediolateral displacement between left and right canter. Right canter featured greater left mediolateral displacement, while left canter featured greater right mediolateral displacement to mimic the directional lean observed during left and right canter in the live horse. A trained attendant controlled the riding simulator.

[Table 1 near here]

Each rider's left and right anterior superior iliac spine and posterior superior iliac spine, and sacrum were palpated. A spherical reflective marker (15 mm diameter) was attached using double-sided tape. Riders wore tight-fitting clothing, their normal riding boots and helmet. A standard 17.5-inch dressage saddle (Devoucoux, Biarritz, France) fitted to the riding simulator was used, and riders adjusted the stirrups to the length of their preference. Riders were acclimated to the riding simulator with a trial run in all gaits until they felt comfortable to perform the test.

Data were captured with nine three-dimensional motion capture cameras (Miqus M3, Qualisys, Gothenburg, Sweden) with a capture rate of 200 Hz. The laboratory axes were right-handed; the x-axis pointed dorsally, the y-axis pointed laterally and to the right and the z-axis pointed cranially.

Riders were first captured for 2 seconds in their normal, seated position at halt. Data were captured for 10 seconds of medium walk, trot, left canter and right canter. Each gait was changed by the riding simulator attendant and signalled to the rider. Riders were instructed to ride the simulator as they would a live horse.

Data analysis

Angular rotation of the pelvis and displacement of the riding simulator were determined from rigid bodies consisting of the markers affixed to the rider’s pelvis and riding simulator, respectively, created in Qualisys Track Manager. Local coordinate systems, which followed the orientation of the global coordinate system, were created for each rigid body. Rotation of the rigid body was defined relative to the global coordinate system and pitch as the second Euler rotation. The recorded pitch of the rider’s pelvis was filtered using a moving average filter with 10 frames in the filter window.

The stride cycle of the riding simulator was defined by the minimum vertical displacement of a cluster of three markers placed on the rear of the simulator. Each pitch measurement was period extracted and normalised to the average minimum-to-minimum period of the simulator’s stride cycle using custom code in MATLAB (The MathWorks Inc., Natick, Mass., USA). The mean, minimum and maximum pelvic pitch values were computed for six strides and averaged for the trial. Given the orientation of the local coordinate system, pitch values of -0.99°–0.99° were designated as neutral pelvic tilt, anterior as values ≤-1.0° and posterior as values ≥1.0°. Pitch range of motion was calculated as the difference between the average minimum and maximum pelvic pitch values.

Statistical analysis

The influence of gait and competition level on mean pelvic tilt, range of motion, and minimum and maximum values were investigated using SPSS, version 26 (IBM Corp., Armonk, N.Y., USA). The hypothesis of normality and homogeneity of variance were analysed for each variable using the Shapiro Wilk test and Levene’s test. A one-way ANOVA was conducted on the influence of the independent variable, competition level (novice, intermediate, advanced), on the mean pelvic tilt in halt and each gait (walk, trot, left canter and right canter). Values were corrected for sphericity using the Huynh-Feldt correction. If a significant *p*-value was obtained for the main or interaction effect of the ANOVA, a *post-hoc* was conducted using a Bonferroni corrected t-test for multiple comparisons. The correlation between mean pelvic tilt in halt, walk, trot, left canter and right canter were calculated using a Pearson's Product Moment test.

Range of pelvic pitching motion (ROM), and minimum and maximum pelvic tilt values were not normally distributed, therefore, differences between these variables across the competition level categories were analysed by separate Independent Samples Kruskal-Wallis Tests. The relationship between halt pelvic tilt values, total range of pelvic pitching motion (ROM), and minimum and maximum pelvic tilt values were analysed by separate Spearman's Rank-Order Correlation tests. The significance level for all tests was set to p <0.05.

Results

[Table 2 near here]

Table 2 shows the mean (± SD) pelvic tilt overall, by competition level at halt, and in each gait. Based on the results of the one-way ANOVA, there were no interaction effects of gait and competition level on mean pelvic tilt ($F_{(3.78,68.18)}$ = 1.35; p = 0.233, η_p^2 = 0.083). The significant main effect of condition (halt, walk, trot, left canter or right canter) ($F_{(2.13,68.18)}$ = 4.48; p = 0.017, η_p^2 = 0.12) on mean pelvic tilt was investigated *post-hoc* using a Bonferroni corrected t-test.

All riders tended to adopt a posterior pelvic tilt as the gait increased. The Bonferroni *post hoc* test indicated that mean pelvic tilt in walk was significantly more anterior than trot (p = 0.039), left canter (p = 0.015) and right canter (p = 0.001), respectively.

At halt, novice riders tended to adopt a posterior pelvic tilt (1.9° ± 4.3), intermediate riders adopted a neutral pelvic tilt (-0.4° ± 5.7) and advanced riders adopted an anterior pelvic tilt (-2.3° ± 3.6), however, there were no significant interactions ($p = 0.233$) between competition level and pelvic tilt. Furthermore, large standard deviation values (listed in Table 2) demonstrate the spread of individual strategies about the central tendency. Correlation coefficients indicated that halt posture did not correlate with pelvic tilt in any gait (halt-walk $r = 0.25$, $p = 0.143$; halt-trot $r = 0.07$, $p = 0.707$; halt-left canter $r = -0.04$, $p = 0.812$, halt-right canter $r = 0.13$, $p = 0.453$). Moderate significant correlations were observed between pelvic tilt in trot and right canter (trot-right canter $r = 0.49$, $p = 0.003$) and large between walk, trot and canter (walk-trot $r = 0.68$, $p = 0.001$; walk-left canter $r = 0.70$, $p = 0.001$; walk-right canter $r = 0.68$, $p = 0.001$; trot-left canter $r = 0.62$, $p = 0.001$; left canter-right canter $r = 0.89$, $p = 0.001$).

Pelvis range of motion

Riders increased their pelvic range of motion as they progressed from walk to trot and both leads of canter. No significant correlations were found between halt pelvic tilt values and ROM in any gait (walk $r = -0.30$, $p = 0.085$; trot $r = 0.10$, $p = 0.572$; left canter $r = -0.15$, $p = 0.397$; right canter $r = -0.10$, $p = 0.557$).

Mean range of motion (± standard deviation) by competition level category is listed in **Table 3** [Table 3 near here]. An Independent Samples Kruskal-Wallis test found no significant differences between competition levels and range of motion in any gait. Greater standard deviation of the mean was observed for novice riders in left canter, while mean range of motion was greater and more variable in right canter for intermediate and advanced riders, although this did not reach statistical significance.

Minimum and maximum tilt values

[Figure 1 and Table 4 near here]

Minimum and maximum values grouped by riders' halt pelvic tilt are displayed in **Figure 1** and data to describe each rider's pelvic strategy are displayed in **Table 4**. Minimum and maximum values were the same across all categories of level, except in right canter, where the maximum value was significantly different between competition level categories ($H(2) = 8.1$, $p = 0.017$). Pairwise comparisons with adjusted p values showed that novice riders' maximum pelvic tilt values were significantly more posterior than advanced riders ($p = 0.016$, $r = 0.33$) and intermediate riders ($p = 0.011$, $r = 0.49$).

No significant correlations were found between pelvic tilt at halt and any minimum or maximum value (walk min-halt $r = -0.004$, $p = 0.983$; walk max-halt $r = -0.10$, $p = 0.582$; trot min-halt $r = -0.06$, $p = 0.745$; trot max-halt $r = -0.05$, $p = 0.778$; left canter min-halt $r = -0.004$, $p = 0.984$; left canter max-halt $r = -0.08$, $p = 0.651$; right canter min-halt $r = -0.27$, $p = 0.125$; right canter max-halt $r = -0.27$, $p = 0.117$).

The dynamic pelvic strategy (Figure 1) was determined from the minimum and maximum pelvic tilt values and described as anterior if their minimum and maximum pelvic tilt values were less than 0º, anterior/posterior if their minimum was less than 0º and maximum greater than 0º, and posterior if their minimum and maximum values were greater than 0º. As a whole, most riders exhibited an anterior/posterior strategy. Outliers indicate that individual strategies in each gait exist. In walk, seven riders remained anterior throughout. Six of these riders were classed as intermediate, three were anterior at halt and three were neutral. One advanced rider was posterior at halt, yet anterior throughout in walk (min: -8.2°, max: -3.9°). In trot, two riders that were classed at halt as posterior and two neutral maintained anterior pelvic tilt throughout the stride. One novice rider, posterior at halt, displayed a large anterior minimum (-13.9°) and near-neutral maximum (-0.9°). One rider with an anterior tilt at halt and one neutral remained posterior throughout. Two intermediate riders, anterior and neutral at halt, respectively, remained anterior throughout.

Discussion and Implications

The lumbopelvic region is the main interface between horse and rider movement. This is the first known study to compare static pelvic posture to pelvic pitching motion in simulated walk, trot and canter across levels of dressage rider. This study aimed to analyse the relationships between gait and competition level on static and dynamic mean pelvic tilt, range of pitching motion, minimum and maximum. It was hypothesised that riders would show common patterns of pelvic tilt, related to competition level. This hypothesis was partially accepted as significant differences between competition levels were observed for maximum pelvic tilt in right canter, however, no other significant differences related to competition level were found.

Comparison between halt pelvic posture and mean pelvic posture in motion

Static assessment of the rider's posture is common in equestrian coaching practice and published research (Guire, Mathie, Fisher, & Fisher, 2017; Hobbs et al., 2014). Assessing the rider in a static position allows the coach to observe the rider's posture closely from all angles, which can be difficult to achieve during riding. Accordingly, as riding is considered a postural sport, it is expected that the rider's seated, static posture will reflect their dynamic patterns (Schiavone & Tulli, 1994). It is assumed that a neutral pelvis and spinal posture are optimal for the rider to absorb the forces generated by the horse without incurring back pain (Wanless, 2017). Previous evidence found significant correlations between pelvic asymmetry in the sagittal plane observed in static seated posture and end of range clinical tests (Al-Eisa, Egan, Deluzio, & Wassersug, 2006), and between pelvic tilt at halt and in the sit phase of rising trot in riders (Gandy et al., 2018). However, in the present study, no dynamic postures were correlated to the rider's halt posture, suggesting that the rider's pelvic tilt in motion is not related to their position at halt. The present results contrast with Gandy et al., (2018), who observed good correlation between anterior-posterior pelvic rotation in rising trot and halt posture. This illustrates differences in the biomechanical demands of rising trot to sitting trot, whereby the rider uses their legs to rise out of the saddle, rather than the lumbopelvic-hip complex to absorb the motion.

Few studies have characterised the pelvic technique of the rider, therefore, anatomical and functional factors relating to the rider's technique are relatively unknown. In the current study, moderate and large significant correlations were observed between mean pelvic tilt in walk, trot, left canter and right canter. This suggests that riders oscillate around a similar mean value in all gaits. As speed increased from walk to trot and canter, a significant increase in posterior pelvic tilt was observed (trot $p = 0.039$; left canter $p = 0.015$; right canter $p = 0.001$). Byström, Roepstroff, Geser-von Peinen, Weishaupt and Rhodin (2015), and Engell, Clayton, Egenvall Weishaupt and Roepstorff (2016) also observed greater posterior pelvic tilt when riders were actively influencing their horse's stride in collected trot or passage, accompanied by greater coupling between horse and rider. Whilst the riders in the present study did not have to initiate upward transitions, as an attendant changed the gaits, the increase in posterior tilt may be a response to the increase in displacement of the simulator, allowing greater coincident movement between horse and rider. Large between-rider variation of the mean tilt indicate that riders possess individual strategies, which are underpinned by variability in the rider's minimum and maximum tilt values in walk, sitting trot and both directions of canter. Further work should aim to investigate the kinematics of the pelvis related to the rider's riding technique, and coincident movement of horse and rider.

Competition level

Previous research has suggested skill-related differences in rider technique (Baillet et al., 2017; Biau et al., 2013; Eckardt & Witte, 2016; Kang et al., 2010; Münz et al., 2014; Olivier et al., 2017; Schils, Greer, Stoner, & Kobluk, 1993). A diverse range of criteria has been used to classify rider skill, including years of experience, competition level and professional status. Statistically significant differences have been found in riders' postural strategy between skill level groups in studies that assessed the coordination between the rider's trunk and the movement of the horse (Baillet et al., 2017; Biau et al., 2013; Lagarde et al., 2005; Münz et al., 2014; Olivier et al., 2017; Peham et al., 2001), but not by Eckardt & Witte (2017). Current research suggests that advanced riders display less variability in their postural strategy (Lagarde et al., 2005), ride the horse closer to their natural, preferred speed (Peham et al., 2001), rely less on visual cues to synchronise their movements with the horse (Olivier et al., 2017), tend to match the oscillation of the horse's trunk with coordinated oscillations of their pelvis (Eckardt & Witte, 2017), and reach maximal dorsal tilt later in the stride in canter than beginner riders (Münz et al., 2014). However, these studies have relied on small sample sizes and, in some cases, different horses for beginner and advanced riders, which influence the demands imposed on each skill group.

In the current study, all riders were exposed to the same oscillation, by using a riding simulator. Contrary to our hypothesis, competition level was not significantly related to halt pelvic posture, dynamic mean pelvic tilt or range of motion (ROM). Competition level influenced maximum pelvic tilt values in right canter only. Novice riders had a significantly ($p = 0.017$) greater posterior maximum pelvic tilt (8.1° ± 3.0) than intermediate (4.9 ° ± 3.6) or advanced (4.4° ± 2.4) riders in right canter. As previously stated, the difference between left and right canter on the riding simulator is marginal (41 mm greater mediolateral displacement to the opposite side). Therefore, differences in the rider's posture between the two leads of canter were surprising. Right-sided asymmetries are common findings in equestrian research. Symes & Ellis, (2009) observed greater chaos of experienced riders' left and right shoulder displacement in right canter on live horses. Münz et al., (2014) also observed significantly greater posterior pelvic tilt in right canter in beginner riders compared to professionals, although their study did not compare right and left canter, therefore it is unclear whether novice riders' posterior pelvic tilt is related to the direction of canter or the asymmetrical movement of canter itself. Interestingly, riders competing at an advanced competition level and those with over 40 years of experience exhibited greater right ROM in a seated lateral flexion test (Hobbs et al., 2014). It is unclear whether directional bias in novice riders results from their individual strategies, amplified by the small number of riders in the novice group (n = 11), thus further investigation is needed.

The present results suggest that once riders achieve the motor control necessary to maintain stability on the horse, that other factors, such as the morphological constraints imposed by mobility, flexibility and patterns of muscle activation, have a greater influence on motion in the sagittal plane than competition level. Intra-subject variation within each competition level, particularly in the minimum and maximum values between each gait, indicates that riders possess individual neuromuscular strategies to achieve and maintain dynamic postural stability on the horse. Many factors may influence the rider's ability to participate in competitions, therefore, individual assessment of biomechanical indicators of rider skill, rather than the use of competition level as a classification factor, may provide greater objectivity in rider assessment and research. Competitive riders may adopt multiple pelvic strategies, however, the classification of rider skill based solely on the pelvis may be reductive. Further studies integrating measures of pelvic tilt into whole-body kinematics of the rider may provide greater evidence towards quantitative assessment of rider skill that is independent of competition level.

Range of motion

Many factors may influence lumbopelvic-hip range of motion (ROM) in riders, including subject-specific characteristics such as age, flexibility, pain, disease and hip morphology (Comerford & Mottram, 2012). The overall mean ROM values found in the present study (walk: 6.9° ± 2.9; trot: 10.1° ± 3.0; left canter: 9.1° ± 3.1; right canter: 9.2° ± 2.9) were smaller than those found in high-level horse and rider pairs in walk (9.7° ± 2.0) and trot (13.9° ± 2.2) by Byström, Rhodin, von Peinen, Weishaupt & Roepstorff (2009, 2010). Similarly, these values were smaller than those found by Münz et al., (2014) in walk (beginner: 8.1° ± 4.1, pro: 11.1° ± 3.6), trot (beginner: 13.5° ± 4.1, pro: 14.8° ± 7.5), and canter (beginner: 22.2° ± 7.8, pro: 18° ± 5). The rider's pelvic range of motion may be most influenced by the horse; therefore, smaller ranges seen in the present study may be due to the use of the riding simulator. No significant differences were found in the present study between ROM and competition level. As the horse dictates the frequency and amplitude of movement, differences between horses may result in varying ranges of rider pelvic rotation.

Riders increased their pelvic ROM as the gait increased. However, no significant correlations were found between halt pelvic tilt values and ROM in any gait. Some evidence suggests that the functional characteristics of the rider's posture may influence available ROM during riding. Alexander et al., (2015) investigated the effects of a taping intervention applied to the rider's thoracic spinal region on their kinematics in sitting trot. Riders exhibited significantly greater lumbar range of motion following the intervention. This evidence suggests that restriction of the thoracic region results in a compensatory increase in lumbar ROM. Sagittal analysis of the rider's pelvis may be insufficient to fully elucidate the patterns of asymmetrical movement in the rider's pelvis and their causes. Further studies should investigate the functional range of motion utilised during riding, within the context of the individual's available range, assessed during a dynamic ROM test and riding.

Minimum and maximum pelvic tilt values

Analysis of the minimum and maximum pelvic tilt values in walk, trot and canter reveal interesting insights into riders' individual postural strategies. There was no relationship between the rider's halt posture and their minimum and maximum pelvic tilt values, which suggests that halt values, do not reflect end ranges of anterior or posterior pelvic tilt during riding in the current study.

Changes in the position of the riders' minimum and maximum pelvic tilt values relative to the neutral origin underline the importance of single-subject analysis. Most riders tended to adopt an anterior/posterior strategy, with a minimum tilt in the anterior range and maximum tilt in the posterior range in each gait. Some riders, however, stayed anterior or posterior throughout the stride. The fluctuation of some riders from posterior pelvic tilt at halt to anterior throughout the stride in walk, to posterior throughout in trot and anterior/posterior in canter reflect individual strategies to remain stable and upright as the horse moves. Maintaining an anterior or posterior pelvic tilt throughout the stride increases the potential for back pain due to compressive and shear forces on the lumbar spine (Norris, 2008). These postural strategies may relate to the individual's learned motor control strategies and segmental control. The position of the pelvis and the phase of the horse's stride influences muscular activation patterns in the trunk and movement of the limbs (Comerford & Mottram, 2012; Terada et al., 2007), therefore, the variety of strategies observed in this study warrant further investigation of their influence on the whole body kinematics of the rider. Moreover, variability in the rider's patterns results from the interactions of the rider's structural and functional characteristics, which, as this study shows, are not evident from static assessment or examination of group means. Further research should aim to understand the factors that influence the rider's strategies and aim to assess whether individuals aggregate around certain factors, which favour group analysis, or whether individual rider strategies are diverse and require single-subject analysis.

Study limitations

Several studies to date have used riding simulators to analyse rider kinematics (Baillet et al., 2017; Biau et al., 2013; Cha, Lee, & Lee, 2016; Olivier et al., 2017; Yoo et al., 2014). However, the differences between rider biomechanics observed on the riding simulator and in field conditions are unknown. Riders in the present study used a generic saddle that was not fitted to the individual rider, although they adjusted the stirrups to their preferred length. The characteristics of the saddle, including seat slope and stirrup length may influence the rider's hip angle and spinal curves (Greve & Dyson, 2013).

5.0 Conclusions

Riders adopt a dynamic technique on a riding simulator that cannot be predicted from their static riding position. Minimum and maximum values can indicate the characteristics of the rider's strategy; whether they maintain an anterior or posterior pelvic tilt throughout, or oscillate between anterior and posterior ranges. However, minimum and maximum values in walk, trot and canter are not associated with halt posture. Assessment of pelvic tilt at halt is insufficient to differentiate between elite and sub-elite riders, and competent riders possess individual strategies that may be obscured by group means. Research should aim to devise quantitative biomechanical indicators of skill that are independent of competition level and that analyse the rider in dynamic, rather than static, conditions.

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Table 1. Movement amplitudes and frequencies of the riding simulator.

	Anterior-Posterior		Mediolateral		Dorsoventral	
Walk	53.3 mm	1.2 Hz	33.9 mm	2.5 Hz	44.6 mm	1.2 Hz
Trot	24.8 mm	0.95 Hz	14.1 mm	2.0 Hz	71.4 mm	0.95 Hz
Canter	100.7 mm	1.1 Hz	8.0 mm	1.2 Hz	69.8 mm	1.1 Hz

Table 2. Mean pelvic tilt values ± standard deviations in halt, walk, left canter and right canter by competition level.

	Overall Mean	**Novice**	**Intermediate**	**Advanced**
Halt	-0.1 ± 4.9°	1.9 ± 4.3°	-0.4 ± 5.7°	-2.3 ± 3.6°
Walk	-0.01 ± 3.3°*	0.4 ± 2.9°	-1.0 ± 3.4°	1.1 ± 3.3°
Trot	1.5 ± 3.3°	1.8 ± 2.6°	0.6 ± 3.5°	2.5 ± 3.7°
Left Canter	1.8 ± 3.8°	1.9 ± 5.0°	1.5 ± 2.7°	2.2 ± 4.1°
Right Canter	2.2 ± 3.6°	2.7 ± 4.5°	2.0 ± 2.6°	1.9 ± 4.2°

[*] Mean significantly ($p<0.05$) different to all other means.

Table 3. Mean range of motion ± standard deviation by competition level category.

	Novice	**Intermediate**	**Advanced**
Walk	7.4 ± 3.4°	6.6 ± 2.7°	6.7 ± 2.7°
Trot	11.2 ± 4.0°	9.4 ± 2.2°	9.9 ± 2.8°
Left Canter	14.1 ± 4.1°	12.9 ± 3.9°	13.2 ± 4.5°
Right Canter	14.0 ± 3.1°	13.6 ± 4.2°	14.6 ± 5.2°

Table 4. As riders progressed through the gaits individuals exhibited unique pelvic tilt strategies. The rider's dynamic pelvic strategy was determined by their minimum and maximum pelvic tilt values. Riders were anterior if their minimum and maximum pelvic tilt values were less than 0º, anterior/posterior if their minimum was less than 0º and maximum greater than 0º, and posterior if their minimum and maximum values were both greater than 0º.

	Pelvic tilt strategy determined by minimum and maximum values				
Competition Level	Halt	Walk	Trot	Left Canter	Right Canter
Novice	anterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	anterior	anterior/posterior	posterior	anterior/posterior	anterior/posterior
	anterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	neutral	anterior/posterior	anterior/posterior	anterior/posterior	posterior
	neutral	anterior/posterior	anterior/posterior	anterior/posterior	posterior
	posterior	anterior/posterior	anterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	posterior	posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
Intermediate	anterior	anterior/posterior	anterior/posterior	posterior	anterior/posterior
	anterior	anterior	posterior	anterior/posterior	anterior/posterior
	anterior	anterior	anterior/posterior	anterior/posterior	anterior/posterior
	anterior	anterior/posterior	anterior/posterior	posterior	anterior/posterior
	anterior	anterior	anterior/posterior	anterior	anterior/posterior
	neutral	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	neutral	anterior/posterior	posterior	anterior/posterior	anterior/posterior
	neutral	anterior	anterior/posterior	anterior	anterior
	neutral	anterior	posterior	anterior/posterior	anterior/posterior
	neutral	anterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	posterior	posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
Advanced	anterior	anterior/posterior	posterior	anterior/posterior	posterior
	anterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	anterior	anterior/posterior	anterior	anterior/posterior	anterior/posterior
	anterior	anterior/posterior	posterior	anterior/posterior	posterior
	anterior	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	neutral	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	neutral	anterior/posterior	anterior/posterior	anterior/posterior	anterior/posterior
	posterior	anterior	anterior/posterior	anterior	anterior/posterior
	posterior	anterior/posterior	posterior	anterior/posterior	anterior/posterior

Figure 1. Riders' minimum and maximum pelvic tilt by halt pelvic posture category in (A) walk, (B) trot, (C) left canter, and (D) right canter, and by competition level category in (E) walk, (F) trot, (G) left canter, and (H) right canter. Posture categories were defined by the rider's pelvic tilt value at halt. Anterior was defined as values of -1º or less, neutral as between 0.99º and -0.99º and posterior as 1º or greater. Competition level categories were defined by the level of their last three results in competition as novice (British Dressage Novice, Preliminary or Elementary), intermediate (British Dressage Medium, Advanced Medium or Advanced) and advanced (FEI Prix St Georges, Inter I or II or Grand Prix).