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Coordination variability reveals the features of the 'independent seat' in competitive dressage riders

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Abstract

The rider's ability to consistently coordinate their movements to their horse is a key determinant of performance in equestrian sport. This study investigated the inter-segmental coordination variability between the vertical displacement of a riding simulator and the pitch rotation of 28 competitive female dressage riders' head, trunk, pelvis, and left foot, in simulated medium and extended trot. A statistical non-parametric mapping three-way repeated-measures ANOVA investigated the influence of gait, competition level and segment on coordination variability. There was a significant main effect of gait and segment ($p = 0.05$), however, no significant effect of competition level. In medium trot, simulator-pelvis coupling was significantly ($p<0.001$) less variable than simulator-head, -trunk, and -foot couplings. Significantly greater coordination variability of simulator-head and -foot relative to the trunk and pelvis suggested that riders can maintain stability in the saddle with their trunk and pelvis while allowing greater variability of their head and foot coupling to the simulator's vertical displacement. It is proposed that stronger coupling of the rider's pelvis relative to their other segments is one facet of the equestrian dressage skill of the independent seat. However, greater perturbations during simulated extended trot may necessitate a decrease in the independence of the rider's seat.

Keywords: Equestrian rider, coordination variability, independent seat, dressage, horse

1. Introduction

Dressage riders aim to give subtle cues so that 'the horse… gives the impression of doing, of its own accord, what is required' (p. 9 Fédération Internationale Équestre, (2020)) during the dressage test. To achieve this, the rider aims to increase the horse's sensitivity to their cues as it progresses in training. The rider applies pressure with their hands on the reins and through their legs onto the horse's side, to cue the horse to change speed or direction. As the horse becomes more sensitive to the rider's cues, the rider can increase their subtlety by giving cues with their seat by varying the pressure and timing of their weight distribution in the saddle. For example, the rider can cue the horse to take shorter steps within a gait by following the horse's movement closely with their pelvis (Engell et al., 2016). The subtlety of the cues to the horse from the rider's seat is contingent on their ability to isolate the movement to their lumbopelvic-hip region. This technique is known as the 'independent seat' (Kottas-Heldenburg & Fitzpatrick, 2014). The independent seat influences the dressage rider's ability to stay in balance without relying on the reins for stability (Zettl, 1998) and gives the impression of a harmonious horse-rider interaction.

To achieve the independent seat, the rider adapts the movement of their pelvis and trunk to match the movement of the horse's trunk and the saddle (Byström et al., 2009, 2010), while isolating the movement produced during the horse's locomotion to their lumbopelvic-hip region to limit the perturbation to their head (Olivier et al., 2017) and hands (Terada et al., 2006). The rider's independent seat must also be adaptable to variations in speed within the gaits of walk, trot and canter. For example, in the two-beat gait of trot, highly-trained dressage horses can produce a medium trot, with speeds around 4.5 m/s^{-1}, or lengthen the stride to produce an extended trot with speeds around 4.9 m/s^{-1} (Clayton, 1994). The rider's ability to adapt their coordination to various gaits and speeds is a necessary component of their riding technique as the dressage competition consists of a floorplan of movements that involve changes between gaits and variations of pace within gaits. The rider must also be able to demonstrate their ability to regulate the horse's movement (Fédération

Internationale Équestre, 2020) by initiating strong horse-rider coupling and maintaining low coordination variability to avoid disruptions to the horse's movement pattern (Peham et al., 2004).

Given the importance of the regularity of the horse's stride on subjective scoring of the dressage test (Fédération Internationale Équestre, 2020), it is feasible that in addition to achieving a baseline coordination of the rider's segments to the horse, the coordination should be consistent from stride-to-stride. Several studies have analysed horse-rider coordination (Eckardt & Witte, 2017; Münz, Eckardt & Witte, 2014; Lagarde et al., 2005; Peham et al., 2001). These studies (Eckardt & Witte, 2017; Münz, Eckardt & Witte, 2014) showed that both novice and professional riders achieve in-phase coordination between the pitching (anterior-posterior rotation) of the horse's trunk and rider's trunk and pelvis. This strategy evidently allows the rider to stay mounted on the horse during movement, however analysing the coordination alone does not reveal the stability of the coordination; how consistent it is between strides.

Only Lagarde et al. (2005) has reported the coordination variability between a horse and multiple rider segments, including the head, arm, hip, and leg, during sitting trot. The vertical displacement of the rider's hip marker was the most in-phase with the vertical displacement of the horse's body, compared to their shoulder, arm and head. Despite differences in the mean relative phase, the coordination variability of these segments was similarly low. This suggests that the professional rider was able to dissociate the movement of the horse from that of their hands and head, but maintain a consistent coupling from stride-to-stride between their segments and the horse, which is the basis for the independent seat. Conversely, the novice rider showed significantly larger coordination variability of their head and arm segments, which reflects their inability to consistently dissociate the movement of the horse from the movement of their trunk and hands. As subsequent studies have focussed on the coordination between a single rider segment such as trunk or pelvis and a horse (e.g. Eckardt & Witte (2017) and Münz, Eckardt & Witte (2014), Wolframm et al. (2013)) there is limited knowledge of how riders achieve balance in the saddle or further descriptions of the independent seat.

In studies of human balance on a moving platform, the segments closest to the platform are the first to react to perturbations (Chen et al., 2014). It follows that to achieve an independent seat the rider must anticipate the horse’s movement with their pelvic region. This is likely a skill developed with practice. For example, experienced riders may exhibit closer coupling between their pelvis and the horse than novice counterparts (Eckardt & Witte, 2017; Münz et al., 2014) and less variability of the angle between their trunk and the horse’s head over a series of strides (Peham et al., 2001). However, the existing evidence does not fully explain how experienced riders self-organise to respond to perturbations caused by the horse and whether differences exist between international and national dressage competitors.

Ko et al. (2001) illustrated the specificity of an individual’s balance strategy to the characteristics of the perturbation. When the frequency and amplitude of anterior-posterior translation of a moving platform were varied, different hip, knee and ankle coordination strategies emerged to reflect the significance of the challenge to the individual’s balance. In dressage riding, riders cue the horse to vary their speed and tempo within a gait and perform transitions between gaits. Therefore, like the findings of Ko et al. (2001), it is expected that dressage riders alter their technique according to the characteristics of the perturbations produced during locomotion. Byström et al. (2015) and Engell et al. (2016) examined high-level riders’ kinematics in several speeds of sitting trot on an equine treadmill. While neither assessed the coordination variability between the rider’s segments and the horse directly, they did find significant differences in the riders’ kinematics between the speeds of trot that indicated that riders positioned themselves differently in the saddle to cue the horse to perform slower or faster trot speeds. It is unclear whether this was precipitated by changes in the perturbations associated with slower or faster trot speed, or whether they related to the rider’s cues to the horse to speed up or slow down. Therefore, a standardised oscillation, similar to the moving platform used by Ko et al. (2001, 2003), and Goldsztein (2016) may help to provide insight into the rider’s balance strategies and help to define the independent seat. The riding simulator is akin to a moving platform that produces similar oscillations to a horse’s trunk during locomotion. Comparisons of novice and expert riders on a riding simulator (Baillet et al., 2017; Olivier et al., 2017) suggest that simulators may be specific enough to discriminate between experience levels. However, it is unclear whether this is still the case between different levels of competitive dressage riders.

The present study aimed to investigate the influence of segment, competition level and gait (medium or extended trot) on the coordination variability of the rider's segments to the riding simulator. As previous research has identified the rider's pelvis as the main coupling interface between horse and rider (Eckardt & Witte, 2017; Münz et al., 2014), it is hypothesised that all riders will show the least continuous relative phase variability of the simulator-pelvis relationship, indicating strong coupling. Previous research suggests an equivocal effect of competition level or rider experience on horse-rider coordination (Eckardt & Witte, 2017), therefore, the relationship between coordination variability and competition level was tested.

2. Materials and Methods

2.1 Participants

Twenty-eight female riders volunteered for the study. Participant characteristics are described in Table 1. Riders were included if they had results in competitions sanctioned by the national equestrian federation, British Dressage (BD), at the levels Medium to Advanced, or in competitions sanctioned by the Fédération International Équestre (FEI), which includes the levels Prix St. Georges to Grand Prix (Olympic level) in the 12 months preceding the data collection. Riders were assigned to one of two groups according to the affiliation of their highest competition level: international (n = 14) if their highest level was FEI-affiliated, and national (n = 14) if their highest level was BD-affiliated. All riders declared that they were free from riding-limiting injuries and each signed informed consent. Ethical approval was granted by the university Ethics Committee.

Table 1. Means ± standard deviation of participant characteristics.

Variable	National level (n = 14)	International level (n = 14)
Age (y)	31 ± 10	33 ± 12
Height (m)	1.69 ± 0.07	1.66 ± 0.08
Mass (kg)	62.5 ± 9.2	63.8 ± 6.5
Competition Levels	BD Medium, Advanced Medium, Advanced	FEI Prix St Georges, Intermediate I and II, Grand Prix

BD: British Dressage, **FEI:** Fédération International Équestre

2.2 Riding Simulator

The riding simulator (Eventing Simulator, Racewood Ltd. Tarporley, Cheshire, UK) moves in three dimensions to simulate a horse's gait. The characteristics of the movement of the riding simulator in medium and extended trot are detailed in Table 2. These variations are set by the manufacturer. Within each of the simulator's gaits, there are variations termed 'collected', 'medium' and 'extended'. As per Table 2, the key difference between medium and extended trot is the 40 mm increase in the anterior-posterior displacement range of motion (ROM) and small (12.45 mm) increase in the vertical displacement ROM. The frequency of the anterior-posterior motion is slightly faster for the riding simulator than dressage horse stride frequencies reported by Clayton (1994) in medium trot (733 ± 17 ms or 1.36 Hz) and extended trot (722 ± 15 ms or 1.39 Hz). However, as stride frequency is related to the size of the horse (Heglund and Taylor, 1988), variation between horses is expected, and the simulator can be likened to representing an average horse.

The same standard dressage saddle (Devoucoux, Biarritz, France) with a 17.5-inch seat was used for all participants. The stirrups were adjusted to the rider's preference. Riders could hold reins that were attached to the head of the riding simulator at the length of their preference but were not instructed to maintain consistent tension on the reins during the trial.

Table 2. Frequency, linear displacement range of motion (ROM) and angular displacement ROM of the riding simulator's medium and extended trot in the anterior-posterior (A-P), lateral, and vertical directions calculated from the rigid body of the simulator.

	Frequency (Hz)			**Displacement ROM (mm)**			**Angular displacement ROM (°)**		
	A-P	**Lateral**	**Vertical**	**A-P**	**Lateral**	**Vertical**	**Roll**	**Pitch**	**Yaw**
Medium	1.73	0.85	1.74	33.6	14.1	71.4	1.10	2.95	1.31
Extended	1.74	0.84	1.74	64.4	13.6	83.9	1.13	1.82	0.66

2.3 Procedure

Three-dimensional kinematic data were collected using a nine-camera motion capture system (Qualisys Miqus M3, Qualisys AB, Gothenburg, Sweden) sampling at 200 Hz. The cameras were positioned around the riding simulator so that all markers could be captured in three dimensions. The capture volume was calibrated so that the origin of the global coordinate system was positioned under the area where the saddle sits during testing. The global coordinate system was defined by the x-axis positive to the rear of the simulator, the y-axis positive to the right, and the z-axis positive upward.

Riders wore tight-fitting riding trousers or leggings, their usual riding boots, a riding helmet and a tight vest top. Spherical reflective markers of 15 mm diameter were affixed with tape to the rider's riding helmet (two anterior, two posterior, one on top of the helmet), upper trunk (markers attached directly to the skin overlying C7, left/right acromion processes, jugular notch; markers attached to an elasticated bandage overlying the mid-back and xiphoid process), pelvis (left/right anterior and posterior superior iliac spines and body of sacrum), and left foot (area of riding boot covering the lateral malleolus, two on the toe of the boot and one on the heel). Three markers were placed on the rear of the riding simulator.

Riders were acclimated to the riding simulator in all gaits for at least five minutes before the trial commenced. A trained attendant controlled the gait of the simulator. Once the rider was comfortable with the riding simulator, data were captured for three seconds to measure the rider's static position in the saddle, and then for 10 seconds of medium and extended trot, respectively. Riders were not given any instructions before or during the data capture other than to 'ride normally'.

2.4 Data Analysis

Rigid bodies were formed from the static capture of the rider for the rider's pelvis, trunk, head and foot, and the riding simulator, in Qualisys Track Manager (Version 2020.1, Qualisys AB, Gothenburg, Sweden). The x, y and z axes of each segment local coordinate system was oriented in the anterior-posterior, medio-lateral and inferior-superior directions, respectively, with the origin at the geometric centre of the markers attached to each segment (Figure 1).

Pitch of the rigid bodies corresponding to the second Euler rotation about the y-axis (rotation in the sagittal plane) using an xyz sequence and the vertical displacement of the riding simulator was calculated in Qualisys Track Manager and exported for further processing in MATLAB (R2020b, The MathWorks, Natick, Mass., USA). Signals were filtered with a 4^{th} order recursive Butterworth filter with a cut-off of 10 Hz determined by visual inspection of a range of cut-off values. They were then split into movement cycles that were defined as the period between two consecutive minimums of the vertical displacement of the riding simulator. Signals were interpolated using linear interpolation and padded to a length of 1001 points in order to avoid spurious variability at the start and end of the signal when calculating the continuous relative phase using the Hilbert transform (Ippersiel et al., 2019).

[Figure 1 near here]

2.5 Coordination variability

Coordination variability was assessed by calculating the variability of the continuous relative phase between the vertical displacement of the riding simulator and the pitch of the rider's head, trunk, pelvis and foot. The riding simulator is not mechanically driven to rotate over a fixed axis in trot, resulting in small pitch ROM values (Table 2). Therefore, as per Lagarde et al. (2005), the vertical displacement of the riding simulator was chosen as the signal to which the rider coordinated their segments. In the live horse, the maximum vertical displacement corresponds to the suspension phase of the gait, while the minimum corresponds to mid-stance (Clayton & Hobbs, 2017).

Simulator-rider coordination was measured over 10 consecutive cycles in medium and extended trot, respectively, for each rider starting from the third valid cycle. As per the recommendations proposed by Lamb & Stöckl (2014), data were normalised and rescaled cycle-by-cycle so that the minimum and maximum values within each cycle corresponded to -1 and 1, respectively. The phase angles were calculated for the head, trunk, pelvis, and riding simulator segments using the Hilbert transform in MATLAB. This approach was chosen as visual inspection of the signals indicated that they were non-sinusoidal. Briefly, the Hilbert transform transforms the data into a complex, analytic signal using the fast Fourier transform and its inverse (Lamb & Stöckl, 2014). The continuous relative phase (CRP) was calculated by determining the difference between the phase angles of the riding simulator relative to the pitch of the rider's head, trunk, pelvis or foot. Coordination variability (CSD_{φ}) was then calculated as the point-by-point circular standard deviation of the CRP for the 10 cycles comprising a rider's trial using a circular statistics toolbox in MATLAB (CircStat, Berens (2009)). This resulted in 28 continuous CSD_{φ} time-series of 1001 samples.

2.6 Statistical analysis

Analysing the CSD_{φ} as a continuous time-series allowed retention of the functional relevance of changes in the level of coordination variability within the cycle. The effect of competition level, segment, and gait on CSD_{φ} over the cycle was analysed using the open-source SPM1D MATLAB package (spm1d.org, Pataky, 2012). The CSD_{φ} data were analysed using one-dimensional statistical non-parametric mapping (SnPM) three-way (level x segment x gait) repeated-measures ANOVA in with >100,000 iterations due to the circular nature of the CSD_{φ} (Pataky et al., 2015). Briefly, SnPM uses Random Field Theory (RFT) to calculate the critical threshold at which α % (in this case, 5%) of smooth random curves would be expected to cross (Adler & Taylor, 2007). If the scalar output statistic calculated separately at each time node exceeds the critical threshold, the null hypothesis is rejected. P-values for each cluster of threshold crosses indicate the probability that supra-threshold clusters could have been produced by a random field process with the same temporal smoothness (Friston, 2003). Supra-threshold clusters exceeding 3% of the total cycle were considered for further interpretation.

As there was a significant main effect of segment and gait. *Post-hoc* SnPM paired *t*-tests were conducted between segments. A type I family-wise error rate of $\alpha = 0.05$ was retained by calculating a Bonferroni correction ($\alpha = 0.008$).

3. Results

The three-way repeated-measures SnPM ANOVA (competition level x segment x gait) (Figure 2) showed a significant main effect for segment ($p = 0.01$, 1-100% of cycle) and gait ($p = 0.01$, 0-15% of cycle; $p = 0.01$, 92-100% of cycle). The significant main effect of gait suggests that overall, was CSD_{φ} significantly decreased at the lowest position of the riding simulator in extended trot. No significant interactions were found.

Post-hoc SnPM t-tests (Figure 3) revealed intersegmental differences in medium and extended trot, respectively. In medium trot, simulator-pelvis CSD_{φ} was significantly ($p < 0.001$) less than simulator-trunk CSD_{φ} from 0-50% of the cycle, which coincided with the ascent phase of the riding simulator's cycle. Simulator-pelvis CSD_{φ} was significantly ($p < 0.001$) less than simulator-head and simulator-foot CSD_{φ} for the entire cycle. Simulator-trunk CSD_{φ} was significantly ($p < 0.001$) less than simulator-head CSD_{φ} from 0-20% of the cycle and 60-100% of the cycle. Simulator-trunk CSD_{φ} was significantly ($p < 0.001$) less than simulator-foot CSD_{φ} from 45-100% of the cycle, which corresponded to the downward portion of the riding simulator's cycle. Simulator-foot CSD_{φ} was significantly ($p < 0.001$) greater than simulator-head CSD_{φ} from 50-75% of the cycle.

[Figure 2 near here]

[Figure 3 near here]

In extended trot, simulator-pelvis CSD_{φ} was less than simulator-trunk CSD_{φ} from 0-50%, however, this did not reach statistical significance. Error cloud plots in Figure 3 suggests that the lack of significant supra-threshold clusters between simulator-pelvis and simulator-trunk in extended trot, compared to medium trot, was due to decreased simulator-trunk CSD_{φ} in extended trot. Simulator-pelvis CSD_{φ} was significantly (p <0.001) less than simulator-head CSD_{φ} from 0-37% of the cycle. Simulator-pelvis CSD_{φ} was significantly (p <0.001) less than simulator-foot CSD_{φ} from 0-100% of the cycle. Simulator-trunk CSD_{φ} was significantly (p <0.001) less than simulator-head CSD_{φ} from 0-100% of the cycle. Simulator-trunk CSD_{φ} was significantly (p <0.001) less than simulator-foot CSD_{φ} from 0-100% of the cycle. No significant differences were found between simulator-head CSD_{φ} and simulator-foot CSD_{φ} in extended trot.

4. Discussion and Implications

This study investigated the influence of simulated medium and extended trot, dressage competition level and rider segment on coordination variability (CSD_{φ}) between the vertical displacement of a riding simulator and the pitch rotation of the rider's head, trunk, pelvis, and left foot. It was hypothesised that the pelvis would exhibit the lowest CSD_{φ}. The hypothesis was partially accepted as the simulator-pelvis coupling exhibited significantly lower coordination variability than the simulator-trunk, simulator-head or simulator-foot couplings in medium trot. However, in extended trot, CSD_{φ} of the simulator-trunk and simulator-pelvis was not significantly different, likely due in part to a non-significant increase in the simulator-pelvis CSD_{φ}. The significant (p = 0.01) main effect of gait at the start and end of the simulator's vertical displacement cycle (0-15% and 92-100%, respectively) corresponds to an overall decrease in CSD_{φ} between medium and extended trot at the lowest vertical position of the riding simulator. The effect of competition level on simulator-segment CSD_{φ} was tested and revealed that competition level was not significantly related to CSD_{φ} in either gait.

The influence of the pelvis on the rider's technique is supported by equestrian coaching (Wanless, 2017) and research that has sought to understand its functional characteristics during riding (Byström et al., 2015; Eckardt & Witte, 2017; Engell et al., 2016; Münz et al., 2014). Of importance is the independence of the rider's seat; that they may follow the movement of the horse with their lumbopelvic-hip complex, while their trunk, hands, feet and head can move independently (Clayton &

Hobbs, 2017). Several authors (Clayton & Hobbs, 2017; Walker et al., 2020) relate the independent seat to the rider's ability to achieve dynamic stability in the saddle. The results presented in this study addressed both the rider's independent seat and the cycle-to-cycle variability of the simulator-rider couplings, which relates to the stability of the rider's technique during the dynamic task of simulated sitting trot.

In order to influence the horse, the rider must achieve consistency in their coupling, as inconsistencies may result in greater variability of the horse's gait (Lagarde et al., 2005). The importance of achieving close horse-rider coupling cannot be understated, as it allows the rider to stay on the horse during riding (de Cocq et al., 2013). In a cohort of experienced riders who are assumed to achieve a sufficient baseline level of coordination to the horse, the coordination variability may be a suitable performance indicator, as it corresponds to the rider's ability to influence the horse's gait rhythm and regularity; one of the subjectively judged parameters within a dressage test (Fédération Internationale Équestre, 2020). The riding simulator follows a similar pattern to the horse's trunk in trot. Unlike a live horse, the variability of the riding simulator itself is low, therefore highlighting variability inherent to the rider.

In the live horse's trot, the ascent of the horse's trunk occurs at late stance of the diagonal limb pairs, with peak vertical displacement occurring during the push-off into suspension (flight) (Clayton, 1994). The descent of the trunk occurs from the suspension phase to mid-stance. The rider's trunk and pelvis pitch posteriorly during the ascent phase, and anteriorly during the descent phase of the stride in sitting trot (Byström et al., 2009). The riding simulator follows a similar pattern of ascent and descent phases during its medium and extended trot. The SnPM analysis allowed the interpretation of the data within the context of the movement cycle. In medium trot, simulator-trunk CSD_{φ} was significantly greater than simulator-pelvis CSD_{φ} during the ascent phase (0-50%) to the point of the change of direction from upward to downward displacement of the riding simulator's movement cycle (Figure 3). No significant differences were found between simulator-trunk and simulator-pelvis CSD_{φ} from 60-

100% of the cycle in medium trot. In extended trot, no significant differences were found between simulator-trunk and simulator-pelvis CSD_{φ} in both ascent and descent phases. Therefore, in simulated medium trot, the rider can allow greater cycle-to-cycle variability of the coupling between the posterior pitch of the trunk, while achieving low variability of the relationship between simulator and pelvis. The descent phase, initiating anterior pitch of trunk and pelvis, appears to be more consistently coupled to the riding simulator in both medium and extended trot. Significantly decreased CSD_{φ} in extended trot suggests that decreasing variability of the anterior pitch of the pelvis, relative to the vertical displacement of the riding simulator, may relate to the rider's balance strategy as the perturbation of the simulator increases.

Significantly greater coordination variability of the simulator-trunk relative to the simulator-pelvis coupling during the ascent phase of the cycle in medium trot may illustrate a facet of the rider's independent seat in this gait. The lower anterior-posterior displacement amplitude of medium trot may permit greater between-cycle variation of the rider's posterior trunk pitch to the ascent phase of the riding simulator, without influencing the stability of the simulator-pelvis coupling. The large spread of the simulator-trunk data in medium trot during the ascent phase, illustrated by the error clouds in Figure 3, indicate individual differences that are likely related to rider characteristics. For example, between-rider differences in motor control (Deckers et al., 2021), standing posture (Hobbs et al., 2014), functional movement test scores (Lewis et al., 2019), and pelvic posture in the saddle (Alexander et al., 2015) have been reported. Decreased coordination variability between trunk and pelvis transverse plane rotations has been observed in humans with low back pain during walking (van den Hoorn et al., 2012). Correlations between rider back pain and altered motor control were reported by Deckers et al. (2021). Although back pain status or spinal motor control were not measured in this study, variability between these competitive riders may relate to differences in rider trunk control perhaps influenced by their history of back pain. Individual differences in the riders' control of trunk posterior pitching moments and the contribution of anthropometric differences between riders could also explain between-rider variation.

In extended trot, no significant differences between the simulator-pelvis and simulator-trunk couplings were apparent. While the significant main effect of gait at the start and end of the cycle suggests that there was an overall decrease in CSD_{φ}, inspection of the plots shows a non-significant decrease in the simulator-trunk CSD_{φ}. This suggested that increasing the anterior-posterior displacement of the riding simulator induced greater stability of the simulator-trunk coupling. Similar findings are reported by Ko et al. (2001) during standing on a platform with varying frequencies and amplitudes of anterior-posterior displacement. They found that as the frequency of the oscillations increased, the participants' platform-ankle and platform-hip coupling variability decreased to stabilise their legs. They also found that the participants invoked coordination strategies that reflected the challenge of the platform's oscillations to their standing balance. For example, at lower oscillation frequencies, the participants invoked an ankle strategy, whereby the other segments were held rigidly, and ankle flexion supported the maintenance of balance. However, as the platform oscillation frequency increased, the participants employed coordinated movements of the hips to keep the centre of mass within the base of support.

Similar to Ko et al. (2001), it appears that riders adopt different coordination strategies depending on the characteristics of the simulator's movement. Riders primarily stabilise their pelvis pitch to the vertical displacement of the riding simulator in medium trot, but increase trunk and pelvis pitch stability to the vertical displacement of the riding simulator in extended trot. As the rider is sitting in the saddle, the pitch rotations of the trunk and pelvis are integral to control the position of the rider's centre of mass (de Cocq et al., 2013). This is similar to how ankles, knees and hips coordinate when standing. As the simulator's anterior-posterior displacement amplitude increased, there was a greater perturbation to the rider's trunk and so they stabilised its coordination to the riding simulator to maintain balance in the saddle. By extension, this preserved the stability of the simulator-pelvis interaction, not only to stabilise the rider's centre of mass but also to maintain control of the seat. Therefore, the pitch rotations of both trunk and pelvis are necessary to maintain balance in the saddle, particularly as the amplitude of the anterior-posterior displacement increased.

Simulator-head and simulator-foot CSD_φ were significantly greater than simulator-pelvis and simulator-trunk CSD_φ in both gaits. Head and foot couplings also displayed observably larger inter-individual differences (Figure 3). This indicated that simulator-foot and simulator-head couplings are less stable than simulator-pelvis and simulator-trunk. Indeed, de-coupling of the head and the foot to the vertical displacement of the simulator could be a functional asset that allows the rider to use their legs and feet to cue the horse's gait and direction, and allows their head to remain stable to facilitate visual perception during riding. No previous studies have analysed the pitch of the rider's foot during sitting trot. However, Lagarde et al. (2005) indicated that professional riders may use rhythmical dorsiflexion and plantarflexion of the foot to dampen the movement of the horse during sitting trot. If that were the case for the present population of riders, lower coordination variability of the foot segment would be expected to indicate simulator-foot coordination, however, this was not the case. Additionally, the riders' foot CSD_φ did not significantly increase between medium and extended trot. The extent of the significant differences within the movement cycle between the simulator-trunk CSD_φ and simulator-foot CSD_φ increased with the gait, likely explained by the decrease in simulator-trunk CSD_φ.

Only Olivier et al. (2017) have investigated head stability in a variety of visual conditions in a simulated gallop. These authors tested the postural stability of Club and professional riders exposed to different visual scenes on a riding simulator in gallop. They found that the displacement of the rider's head was significantly more variable than their lumbar spine in the vertical and mediolateral axes, but not the anterior-posterior axis. In the present study, the pitch of the rider's head in sitting trot was analysed which could explain the contrast between these results and Olivier et al. Significantly less stability of the couplings between the simulator-head and foot relative to simulator-pelvis (Figure 3) may indicate that these segments may be influenced by other planes/axes of simulator movement. It is also possible that the cyclical movement of the simulator, rather than the forward travel and ground reaction forces produced by the live horse during locomotion, resulted in greater instability of the coupling between simulator-foot and simulator-head. In the present study, riders were not required to actively cue the simulator to maintain its speed with their legs or use optical flow information during the task. As coordination patterns can be task-specific (Renshaw et al., 2010), increased variability of the head and foot may be related to the task of riding the simulator, and further work is needed to replicate these results in riders on live horses.

To date, variability in equestrian rider technique has been perceived as detrimental to performance and attributed to lack of rider skill (Lagarde et al., 2005; Peham et al., 2004). As horses and riders are biological systems, some inherent variability is expected between movement cycles. Previous studies analysing horse-rider coordination have typically adopted the novice-expert paradigm (Eckardt & Witte, 2017; Lagarde et al., 2005; Münz et al., 2014; Peham et al., 2001), which infers that the coordination between horse and rider is determined by the single constraint of rider experience. However, the perception of the task of riding may be drastically different between novice and professional riders. In this study, the task was standardised between participants by using a riding simulator. Significant differences between competition level categories for any simulator-segment CSD_{φ} were not found between national and international dressage riders in the controlled environment of the riding simulator. Once riders have entered the lowest levels of national competition, their ability to coordinate with a horse or riding simulator has likely been established, so other factors inherent to the rider may have a greater influence on their coordination patterns as they ride passively on a riding simulator. Therefore, further research should aim to establish other grouping factors that do not relate to competition level when investigating experienced riders.

This study underlined the importance and expanded on the role of the pelvis to the rider's self-organisation as they performed simulated sitting trot and offered a new variable: the circular standard deviation of the continuous relative phase. The CSD_{φ} measured the stability of the coordination between the rider's segments and the simulator during the movement cycle. The rhythm and regularity of the horse's gait have a substantial bearing on the performance outcomes in dressage (Fédération Internationale Équestre, 2020). The rider can influence the horse's gait with their pelvis

(Byström et al., 2015; Engell et al., 2016) and regulate the horse's gait variability with their overall technique (Peham et al., 2004). Therefore, the simulator-pelvis CSD_{φ} described the quality of the rider's pelvis technique and is a relevant parameter to analyse horse-rider interaction. It is important to note that this variable is derived from the circular standard deviation of the continuous relative phase, which is a higher-order variable that compresses the angular (rider segments) or linear (riding simulator) displacement and corresponding angular or linear velocity of each coupling pair into a single continuous time-series. The CSD_{φ} indicates the stability of the coordination but does not provide any information to describe the orientation of the pelvis. Different pelvis orientations may give rise to similarly stable coupling patterns (e.g. motor equivalence), although they may not be viewed as optimal from an aesthetic or injury prevention perspective (Glazier & Davids, 2009). Further investigation of the influence of the pelvis orientation on measures of coordination variability is warranted.

5. Conclusions

In conclusion, these results captured the underlying variability of multiple simulator-rider couplings and provided an insight on one facet of the rider's independent seat: their ability to maintain a strong and stable coupling of the pelvis to the riding simulator, but allow variability within their head, trunk and foot. The pelvis displayed the strongest coupling to the riding simulator, which was resilient to changes in the amplitude of anterior-posterior displacement from medium to extended trot. Weaker coupling of the head and feet to the vertical displacement of the riding simulator indicated that the rider achieved enough stability by initiating coincident movement of the pelvis and trunk, so that variability at the extremities did not diminish the rider's stability in the saddle. Decreased simulator-trunk CSD_{φ} in extended trot suggested that the rider maintained the stability of their seat by initiating stronger coupling between their trunk and the vertical displacement of the simulator as the amplitude of anterior-posterior displacement increased. Therefore, strength of coupling, and therefore the independence of the seat, may decrease as the characteristics of the horse's gait changes to allow the rider to remain in balance. Further studies should investigate the coordination between horse or riding simulator and rider further, focussing on phase shift and the position of the pelvis to fully characterise the independent seat.

References

Adler, R. J., & Taylor, J. E. (2007). Random Fields and Geometry. In *Random Fields and Geometry* (1st ed.). Springer New York. https://doi.org/10.1007/978-0-387-48116-6_1

Alexander, J., Hobbs, S. J., May, K., Northrop, A., Brigden, C., & Selfe, J. (2015). Postural characteristics of female dressage riders using 3D motion analysis and the effects of an athletic taping technique: A randomised control trial. *Physical Therapy in Sport*, *16*(2), 154–161. https://doi.org/10.1016/j.ptsp.2014.09.005

Baillet, H., Thouvarecq, R., Vérin, E., Tourny, C., Benguigui, N., Komar, J., & Leroy, D. (2017). Human energy expenditure and postural coordination on the mechanical horse. *Journal of Motor Behavior*, *49*(4), 441–457. https://doi.org/10.1080/00222895.2016.1241743

Berens, P. (2009). *CircStat: A MATLAB toolbox for circular statistics*. MATLAB Central File Exchange. https://www.mathworks.com/matlabcentral/fileexchange/10676-circular-statistics-toolbox-directional-statistics

Byström, A., Rhodin, M., von Peinen, K., Weishaupt, M., & Roepstorff, L. (2009). Basic kinematics of the saddle and rider in high-level dressage horses trotting on a treadmill. *Equine Veterinary Journal*, *41*(3), 280–284. https://doi.org/10.2746/042516409X394454

Byström, A., Rhodin, M., von Peinen, K., Weishaupt, M., & Roepstorff, L. (2010). Kinematics of saddle and rider in high-level dressage horses performing collected walk on a treadmill. *Equine Veterinary Journal*, *42*(4), 340–345. https://doi.org/10.1111/j.2042-3306.2010.00063.x

Byström, A., Roepstroff, L., Geser-von Peinen, K., Weishaupt, M., & Rhodin, M. (2015). Differences in rider movement pattern between different degrees of collection at the trot in high-level dressage horses ridden on a treadmill. *Human Movement Science*, *41*, 1–8. https://doi.org/https://doi.org/10.1016/j.humov.2015.01.016

Chen, C. L., Lou, S. Z., Wu, H. W., Wu, S. K., Yeung, K. T., & Su, F. C. (2014). Effects of the type and direction of support surface perturbation on postural responses. *Journal of NeuroEngineering and Rehabilitation*, *11*(50), 1–12. https://doi.org/10.1186/1743-0003-11-50

Clayton, H. M. (1994). Comparison of the stride kinematics of the collected, working, medium and extended trot in horses. *Equine Veterinary Journal*, *26*(3), 230–234. https://doi.org/10.1111/j.2042-3306.1994.tb04375.x

Clayton, H. M., & Hobbs, S. J. (2017). The role of biomechanical analysis of horse and rider in equitation science. *Applied Animal Behaviour Science*, *190*, 123–132. https://doi.org/10.1016/j.applanim.2017.02.011

de Cocq, P., Muller, M., Clayton, H. M., & van Leeuwen, J. L. (2013). Modelling biomechanical requirements of a rider for different horse-riding techniques. *The Journal of Experimental Biology*, *216*(10), 1850–1861. https://doi.org/10.1242/jeb.070938

Deckers, I., De Bruyne, C., Roussel, N. A., Truijen, S., Minguet, P., Lewis, V., Wilkins, C., & Breda, E. Van. (2021). Assessing the Sport-Specific and Functional Characteristics of Back Pain in Horse Riders. *Comparative Exercise Physiology*, *17*(1), 7–15. https://doi.org/10.3920/CEP190075

Eckardt, F., & Witte, K. (2017). Horse–rider interaction: A new method based on inertial measurement units. *Journal of Equine Veterinary Science*, *55*, 1–8. https://doi.org/10.1016/j.jevs.2017.02.016

Engell, M. T., Clayton, H. M., Egenvall, A., Weishaupt, M., & Roepstorff, L. (2016). Postural changes and their effects in elite riders when actively influencing the horse versus sitting passively at trot. *Comparative Exercise Physiology*, *12*(1), 27–33. https://doi.org/10.3920/CEP150035

Fédération Internationale Équestre. (2020). *Dressage Rules*. Fédération Internationale Équestre.

Friston, K. J. (2003). Statistical Parametric Mapping. In *Neuroscience Databases* (pp. 237–250). Springer US. https://doi.org/10.1007/978-1-4615-1079-6_16

Glazier, P. S., & Davids, K. (2009). Constraints on the complete optimization of human motion. *Sports Medicine*, *39*(1), 15–28. https://doi.org/10.2165/00007256-200939010-00002

Goldsztein, G. H. (2016). Reactions of standing bipeds on moving platforms to keep their balance may increase the amplitude of oscillations of platforms satisfying Hooke's law. *PLoS ONE*, *11*(6), 1–17. https://doi.org/10.1371/journal.pone.0157675

Heglund, N.C. and Taylor, C.R. (1988) Speed, stride frequency and energy cost per stride: how do they change with body size and gait? *Journal of Experimental Biology*. 138, pp. 301-318.

Hobbs, S. J., Baxter, J., Broom, L., Rossell, L.-A., Sinclair, J., & Clayton, H. M. (2014). Posture, flexibility and grip strength in horse riders. *Journal of Human Kinetics*, *42*(1), 113–125. https://doi.org/10.2478/hukin-2014-0066

Ippersiel, P., Preuss, R. & Robbins, S.M. (2019) The effects of data padding techniques on continuous relative-phase anlaysis using the Hilbert transform. *Journal of Applied Biomechanics*. 35, pp. 247-255. https://doi.org/10.1123/jab.2018-0396

Ko, Y. G., Challis, J. H., & Newell, K. M. (2001). Postural coordination patterns as a function of dynamics of the support surface. *Human Movement Science*, *20*(6), 737–764. https://doi.org/10.1016/S0167-9457(01)00052-5

Ko, Y. G., Challis, J. H., & Newell, K. M. (2003). Learning to coordinate redundant degrees of freedom in a dynamic balance task. *Human Movement Science*, *22*(1), 47–66. https://doi.org/10.1016/S0167-9457(02)00177-X

Kottas-Heldenburg, A., & Fitzpatrick, A. (2014). *Dressage Solutions A Rider's Guide*. Kenilworth Press.

Lagarde, J., Peham, C., Licka, T., & Scott Kelso, J. A. (2005). Coordination dynamics of the horse-rider system. *Journal of Motor Behavior*, *37*(6), 418–424. https://doi.org/10.3200/JMBR.37.6.418-424

Lamb, P. F., & Stöckl, M. (2014). On the use of continuous relative phase: Review of current approaches and outline for a new standard. *Clinical Biomechanics*, *29*(5), 484–493. https://doi.org/10.1016/j.clinbiomech.2014.03.008

Lewis, V., Douglas, J. L., Edwards, T., & Dumbell, L. (2019). A preliminary study investigating functional movement screen test scores in female collegiate age horse-riders. *Comparative Exercise Physiology*, *15*(2), 105–112. https://doi.org/10.3920/CEP180036

Münz, A., Eckardt, F., & Witte, K. (2014). Horse-rider interaction in dressage riding. *Human Movement Science*, *33*, 227–237. https://doi.org/10.1016/j.humov.2013.09.003

Olivier, A., Faugloire, E., Lejeune, L., Biau, S., & Isableu, B. (2017). Head stability and head-trunk coordination in horseback riders: The contribution of visual information according to expertise. *Frontiers in Human Neuroscience*, *11*(11), 1–16. https://doi.org/10.3389/fnhum.2017.00011

Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer methods in biomechanics and biomedical engineering*, 15(3), 295-301.

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero-vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*, 48(7), 1277-1285.

Peham, C., Licka, T., Kapaun, M., & Scheidl, M. (2001). A new method to quantify harmony of the horse-rider system in dressage. *Sports Engineering*, *4*(2), 95–101. https://doi.org/10.1046/j.1460-2687.2001.00077.x

Peham, C., Licka, T., Schobesberger, H., & Meschan, E. (2004). Influence of the rider on the variability of the equine gait. *Human Movement Science*, *23*(5), 663–671. https://doi.org/10.1016/J.HUMOV.2004.10.006

Renshaw, I., Davids, K., & Savelsbergh, G. J. P. (2010). Motor Learning in Practice. In *Motor Learning in Practice*. Routledge. https://doi.org/10.4324/9780203888100

Terada, K., Clayton, H., & Kato, K. (2006). Stabilization of wrist position during horseback riding at trot. *Equine and Comparative Exercise Physiology*, *3*(4), 179–184. https://doi.org/10.1017/s1478061506337255

van den Hoorn, W., Bruijn, S. M., Meijer, O. G., Hodges, P. W., & van Dieën, J. H. (2012). Mechanical coupling between transverse plane pelvis and thorax rotations during gait is higher in people with low back pain. *Journal of Biomechanics*, *45*(2), 342–347. https://doi.org/10.1016/j.jbiomech.2011.10.024

Walker, V. A., Pettit, I., Tranquille, C. A., Spear, J., Dyson, S. J., & Murray, R. C. (2020). Relationship between pelvic tilt control, horse-rider synchronisation, and rider position in sitting trot. *Comparative Exercise Physiology*, *16*(5), 1–10. https://doi.org/10.3920/cep190071

Wanless, M. (2017). *The New Anatomy of Rider Connection*. Trafalgar Square.

Wolframm, I. A., Bosga, J., & Meulenbroek, R. G. J. (2013). Coordination dynamics in horse-rider dyads. *Human Movement Science*, *32*, 157–170. https://doi.org/10.1016/j.humov.2012.11.002

Zettl, W. (1998). *Dressage in Harmony: from Basic to Grand Prix*. Half Halt Press, Inc.

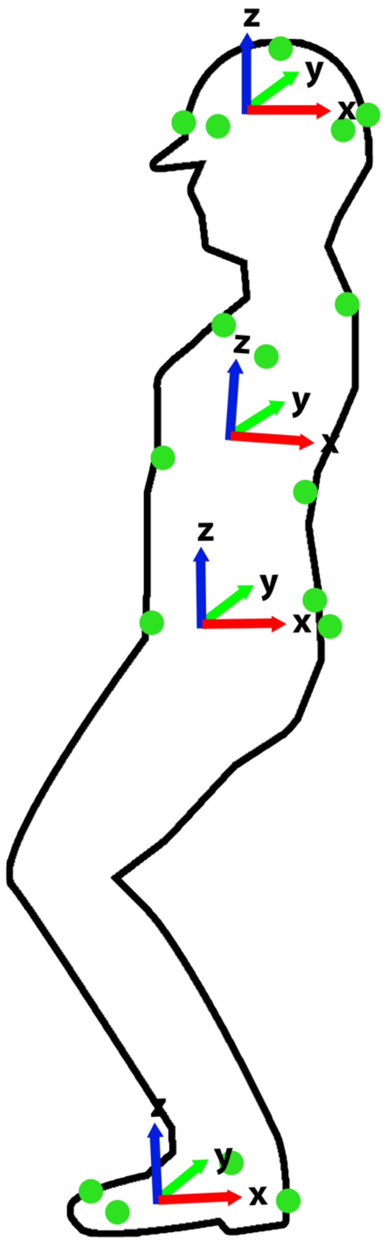

Figure 1. Position and orientation of the local coordinate systems for the rigid bodies of the head, trunk, pelvis, and foot.

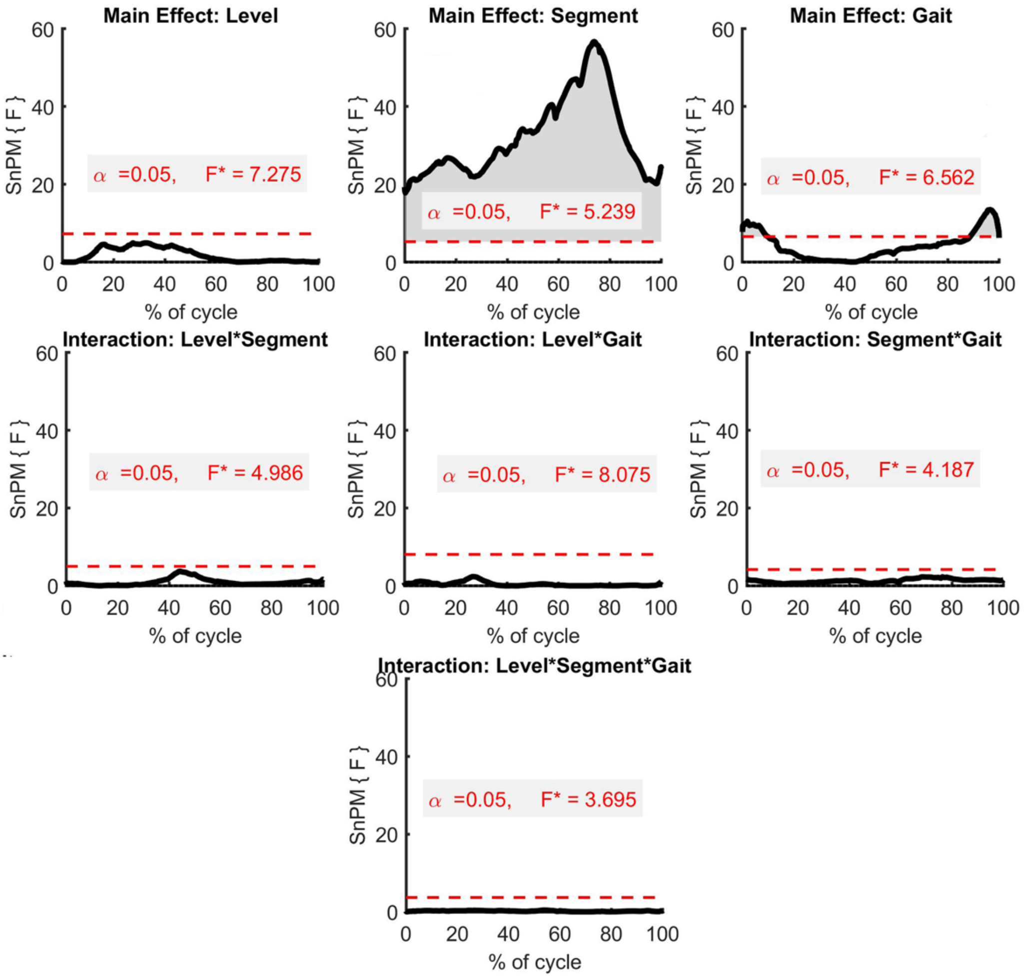

Figure 2. Results of three-way repeated-measures SnPM ANOVA on simulator-segment CSD_{φ} by segment (pelvis, trunk, head and foot), by level (national, international) and gait (medium and extended trot). *F*(t) trajectory (black) and corresponding critical thresholds calculated using random field theory (horizontal dashed lines) for the main effect of level, the main effect of segment and interactions. Shaded areas indicate supra-threshold clusters with significance at the level of $p = 0.01$. Data are plotted to a percentage of the overall movement cycle (minimum-to-minimum vertical displacement) of the riding simulator.

NB: critical threshold values vary as they represent the critical threshold at which α % (in this case, 5%) of smooth random curves would be expected to cross.

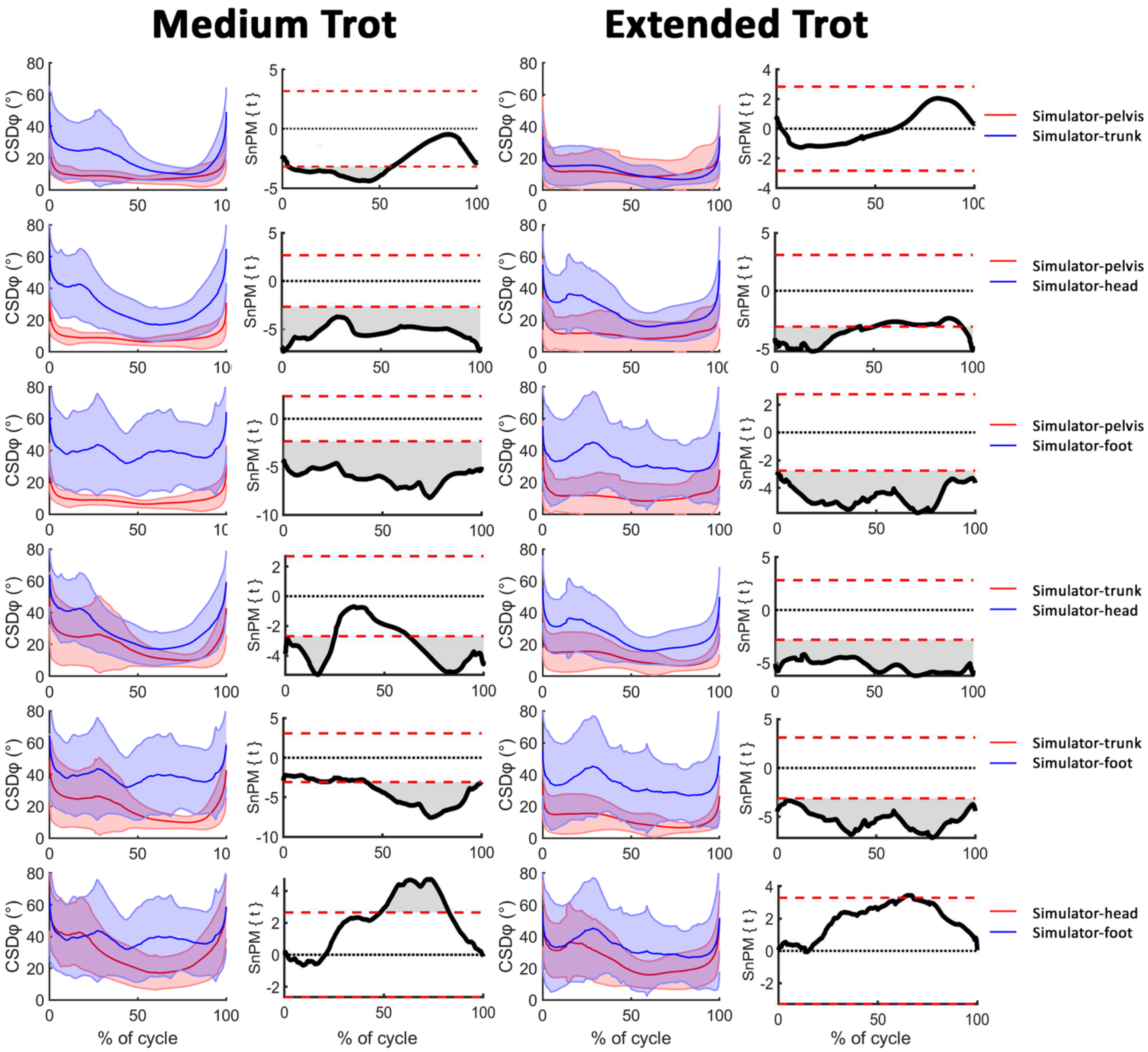

Figure 3. Results of the post-hoc Bonferroni-corrected SnPM paired t-tests in medium (left) and extended (right) trot. Group mean and error cloud CSD_{φ} trajectories for the paired segments (legend to far right) to the left of corresponding SnPM T(t) trajectories. Dashed lines indicate corresponding critical thresholds on SnPM plots, while shaded areas indicate supra-threshold clusters with significance at the level of p <0.001. Colour figure available online.