biomechanics

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Segmental and Intersegmental Coordination Characteristics of a Cognitive Movement Control Test: Quantifying Loss of Movement Choices

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Abstract: Cognitive movement control tests are hypothesized to reveal reduced coordination variability, a feature of motor behaviour linked to clinical presentations. Exploration of this proposition via kinematic analysis of test pass and fail conditions is yet to be conducted. Kinematics (3D) were collected as 28 participants were qualitatively rated during nine trials of a cognitive movement control test. Ten female and two male participants passing the test were matched to twelve participants who failed (three males, nine females). Sagittal plane pelvis and knee angles were determined. Peak pelvic deviation and knee flexion maxima/minima were compared between groups. Classification tree analysis explored relationships between test failure and pelvis–knee intersegmental coordination strategy classifications derived from novel and traditional vector coding techniques. Coordination variability waveforms were assessed via SPM. Age, BMI, and knee flexion values did not differ between the groups ($p > 0.05$); however, participants rated as failing the test displayed greater pelvic deviation ($p < 0.05$). Classification tree analysis revealed a greater use of pelvic dominant intersegmental coordination strategies from both vector coding techniques ($p < 0.001$) by fail-group participants. The fail-group also displayed lower coordination variability for novel ($p < 0.05$), but not traditional ($p > 0.05$) vector coding technique waveforms, supporting the premise that the testing protocol may act as a qualitative approach to inform on features of motor behavior linked to clinical presentations.

Keywords: vector coding; coordination variability; movement assessment; anterior pelvic tilt

Citation: Blandford, L.; Cushion, E.; Mahaffey, R. Segmental and Intersegmental Coordination Characteristics of a Cognitive Movement Control Test: Quantifying Loss of Movement Choices. *Biomechanics* **2022**, *2*, 213–234. https://doi.org/10.3390/biomechanics2020018

Academic Editor: Justin Keogh

Received: 12 February 2022
Accepted: 11 May 2022
Published: 13 May 2022

1. Introduction

For clinicians working within the musculoskeletal health domain, the assessment of coordination strategies represents a fundamental skill and one identified to support the clinical reasoning process [1,2]. Yet within clinical environments coordination strategies are qualitatively assessed, a process dependent upon practitioners' visual appraisal of patient performance [3–5]. Though less burdened by the financial and time constraints associated with quantitative techniques [5,6], qualitative assessment protocols' subjectivity elicits criticism [7,8]. Indeed, as qualitative assessment steers practitioners' decision making and guides patient interventions [9–11] calls for greater quantification gain justification.

Cognitive movement control tests (CMCT) are a qualitative assessment protocol requiring practitioners to rate features of patients' motor control [4,12,13]. Specifically, CMCTs question the ability to consciously prevent a segment of interest from deviating into a specific trajectory, while reaching a mandatory benchmark range of motion (ROM) at another segment or joint articulation [4,12]. The testing protocol, therefore, requires practitioners to focus on motion trajectories and motion amplitudes at both the segmental and intersegmental levels. Failure of CMCTs has been operationally defined as a loss of movement choice (LMC) [14]. Proposing the LMC Hypothesis, Mottram and Blandford [14] suggest each LMC represents reduced coordination variability (CoV), as participants failing CMCTs are unable to prevent using a specific coordination strategy when instructed. Reduced CoV is linked to the presence of clinical presentations and pathology [15] and is hypothesised to raise injury risk [16,17]. The appraisal of CoV within clinical environments remains an unrealised goal [18], currently only achievable within research laboratories. Clinical presentations seen to accompany CMCT failure [9,11,19,20] may be linked to the presence of reduced CoV. Yet, while CMCTs may deliver insight on a 'macroscopic' version of CoV, associations between the presence of LMC and reduced trial-to-trial variation in coordination strategies remain unexplored.

The performance matrix is a battery of 10 CMCTs [21] that has demonstrated good to excellent inter-rater and intra-rater reliability [22]. Frequently described within the literature [2,14,19–24], the testing battery has considered a range of populations including athletes within both team [19] and individual sports [20], military personnel [23], and ballet performers [24]. The bilateral partial squat is the first testing item of the performance matrix and explores the ability to prevent observable anterior pelvic tilt trajectory motion while achieving a benchmark ROM of knee flexion [4,22,25]. The literature highlights the relevance of considering coordination strategies that include an anterior pelvic tilt and lower extremity motion with respect to clinical presentations and conditions such as hamstring muscle injury [26–29] and femoro-acetabular impingement syndrome [30–32]. Therefore, tools to appraise sagittal plane pelvic and lower extremity coordination possess clinical value. With respect to the validity of the bilateral partial squat, Whatman et al. [33] compared raters' qualitative assessment of participant performance against 3D motion capture technology [33]; however, only frontal and transverse plane kinematics were explored. In cases where sagittal plane pelvis kinematics have been quantified, the CMCT literature has focused on unilateral as opposed to bilateral squats [11,34]. Therefore, kinematics exploring rater interpretation of the bilateral partial squat as seen within the performance matrix (sagittal plane) are yet to be reported. The coordination challenge of the bilateral partial squat, (e.g., knee flexion in the absence of observable anterior pelvic tilt) may also allow between-group distinctions in coordination to be revealed not only at the segmental (pelvis) but also at the intersegmental level (pelvis–knee). Identification of segmental and intersegmental kinematic distinctions between participants passing or failing the test would support the exploration of whether test failure is also accompanied by reduced CoV as proposed by the LMC Hypothesis [14].

The study aimed to perform a between-group analysis on the kinematics of participants qualitatively rated as passing or failing the bilateral partial squat. The first aim of this study was to quantify differences in the peak pelvic deviation in the bilateral partial squat between participants who passed as compared to those who failed the test. Hypothesis 1 proposed those rated as failing the bilateral partial squat would display greater pelvic segment deviation. Reflective of CMCTs' coordination challenge, Hypothesis 2 compared intersegmental coordination strategies (pelvis and knee). Hypothesis 2 stated that participants failing the test (displaying more pelvic deviation) would show a greater use of anterior pelvic tilt dominant pelvis and knee coordination strategies. Finally, Hypothesis 3 compared trial-to-trial variation in bilateral partial squat execution. Hypothesis 3 stated that test failure would be accompanied by reduced CoV of the pelvis and knee as proposed by the LMC Hypothesis. In summary, the investigation aimed to quantify segmental and intersegmental coordination during the first testing item of a long-established qualitative approach and inform the LMC Hypothesis.

2. Materials and Methods

2.1. Participants

Nine male and nineteen female participants, with a mean age of 38.06 years (8.59) and BMI of 23.73, (2.63) were recruited from the local community. Participants were excluded if injured, presenting with pre-existing medical conditions, or having undergone recent lower limb surgery. Participants were advised to avoid strenuous exercise for 48 h pretesting. Ethical approval was granted by St Mary's University Ethics Committee prior to recruitment. Participants provided informed consent for the study.

2.2. Testing Procedure

For each trial of the bilateral partial squat, participants stood with their feet parallel (approximately 15 cm apart) prior to rotating their pelvis, anteriorly and posteriorly, at a comfortable, self-selected pace [4,25]. In accord with Mottram and Blandford [14] a pelvic alignment representing the midpoint between a full anterior and posterior pelvic tilt was identified for each participant. Participants were then instructed to keep the trunk upright and to prevent the heels from lifting as they performed the bilateral partial squat (Figure 1). An experienced tester made a qualitative judgement of whether the pelvis displayed an anterior trajectory of deviation during the test and ensured each participant achieved the test's benchmark of ROM (knees five centimetres beyond second toe). Pelvis and knee kinematics were captured simultaneously, in accord with Wilson et al. [11]. An inability to prevent observable pelvic deviation during the test was identified as LMC [14]. Individuals displaying LMC were identified as CMCT-fails. Prior to data capture, and to increase the likelihood of an accurate rating of test performance, participants practiced the bilateral partial squat three to six times, receiving feedback from the tester who verbally checked participants' understanding of the test's requirements [23].

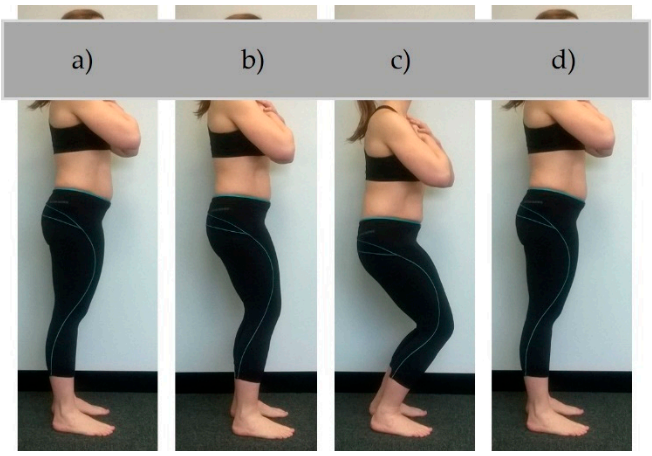

Figure 1. Bilateral partial squat phase identification. (**a**) start position; (**b**) termination of pelvic tilt; (**c**) maximum knee flexion; (**d**) minimum knee flexion. Descent phase represents epoch from termination of pelvic tilt (**b**) to the knee flexion maximum value (**c**); ascent phase represents instant at which knee extension commenced (**c**) to minimum knee flexion value (**d**).

2.3. Data Collection

Three-dimensional kinematic data were collected via opto-electronic stereophotogrammetric technology (Vicon MX System, Nexus 2.2 software, Vicon Motion Systems Ltd., Oxford, UK) with 14 infrared cameras at a sampling frequency of 200 Hz. Cameras were calibrated and the origin of the global coordinate system (laboratory) was defined, following the axes convention Y (flexion/extension), X (abduction/adduction), and Z (axial rotation). Static and dynamic trials were collected in accord with the modified Instituto Ortopedico Rizzoli (IOR) model [35]. Static trial capture saw participants assume anatomical neutral positions, once plate-mounted reflective cluster tracking markers (marker size, 14 mm) were firmly attached to the thigh, shank, and pelvis. An anatomical landmark calibration procedure was conducted via a spring-activated pointer device (C-Motion. Inc., ON, Canada) applied sequentially to the following bony anatomical landmarks: anterior superior iliac spine, posterior superior iliac spine, greater trochanter, medial knee, lateral knee, tibial tuberosity, head of fibula, lateral malleolus, medial malleolus [36]. Dynamic trial performance followed.

2.4. Data Processing

For reconstruction of segment motions, a Cardan rotation sequence was performed following the convention Z, X, and Y, corresponding to the sagittal, frontal, and transverse planes, respectively [35]. Knee joint motion was reconstructed about the local coordinate system of the shank relative to the thigh. Pelvis kinematics were computed by reconstructing pelvic frame motion (distal segment) relative to the global coordinate system (laboratory, following Baker [37]. To permit merging of calibration and movement data, the calibrated anatomical system technique procedure transformed anatomical landmarks from the cluster marker of interest to the global coordinate system via a combination of cluster-based and virtual makers in Visual 3D (C-Motion. Inc., Mississiauga, ON, Canada). Marker trajectories were filtered using a low-pass, fourth-order Butterworth filter with a cut-off frequency of 6 Hz [38]. All trials were normalised to 101 time points. Visual inspection of plots and marker trajectories (lateral epicondyle) via Vicon Nexus software, allowed for the identification of the start and termination of descent and ascent phases, respectively (Figure 1). King and Hannan [39] reported nine trials are required to capture the range of coordination strategies employed during body weight squats. Within the present study, 10 bilateral partial squat trials were captured, accommodating capture errors. Indeed, due to missing data, nine trials were used for analysis. To inform on Hypothesis 1, pelvic deviation from the participant's neutral alignment (pass/fail relevant kinematics) was determined. Additionally, knee flexion amplitudes were determined to identify if participants reached the test's benchmark of ROM and to permit the exploration of Hypothesis 2 and 3. Discrete variables (ii–iv) extracted from each phase for analysis, are detailed in Section 2.6.

2.5. Data Analysis

2.5.1. Vector Coding Techniques

With respect to Hypothesis 2, intersegmental coordination of the pelvis and knee during the bilateral partial squat was quantified via vector coding techniques. The bilateral partial squat requires clinicians to simultaneously rate pelvic deviation during the achievement of a mandatory benchmark of knee flexion [25]. Therefore, clinicians must focus on motion trajectories and displacements of separate body regions over the full duration of the test. Vector coding techniques allow for the quantification of the relative motion of segments during the entirety of a task's execution [40,41]. Vector coding generates coupling angles (∅), representing a time-varying, ratio of excursion of the pelvis and knee [40,41]. Coupling angle values of either 90° or 270° represent coordination strategies in which motion only occurs at the knee during a squat's descent and ascent phase, respectively (Figure 2b). Therefore, such coordination strategies represent optimal performance (no pelvic deviation, accompanying knee flexion, or extension) of the bilateral partial squat. Each coupling angle derived from the vector coding technique, therefore, quantifies the participants' success or failure in producing motion at one region while aiming to prevent motion at another. Furthermore, the rater's ability to differentiate between those passing and failing the test is also revealed in a metric (coupling angle) representative of the CMCT protocol's instructions (pelvis deviation relative to knee motion).

To generate coupling angles, angle–angle plots were created in which the proximal (pelvis) and distal (knee) joint kinematic data were plotted on the x- and y-axes (Figure 2a), respectively [40]. Subsequently, for each instant (i), where 'i' represents each percent of the test of the 'j^{th}' trial, angles from the right horizontal of the vector connecting consecutive proximal segmental angles (x) and consecutive distal segmental angles (y), were calculated (1). Conditions were applied (2), that corrected for negative coupling angle values and occasions in which the value zero appeared as the denominator. Therefore, coupling angle values at each time point, for each trial ($\varnothing_{\mathrm{j,\,i}}$) were determined. Figure 2b identifies positive segment/joint rotations indicating anterior pelvic tilt and knee flexion; negative values represent posterior pelvic tilt and knee extension. Though frequently described as modified vector coding [42], the methods aforementioned of determining coupling angles are here described as consecutive vector coding (ConVC) so as to distinguish between a further modification (target-alignment vector coding) employed within the present work.

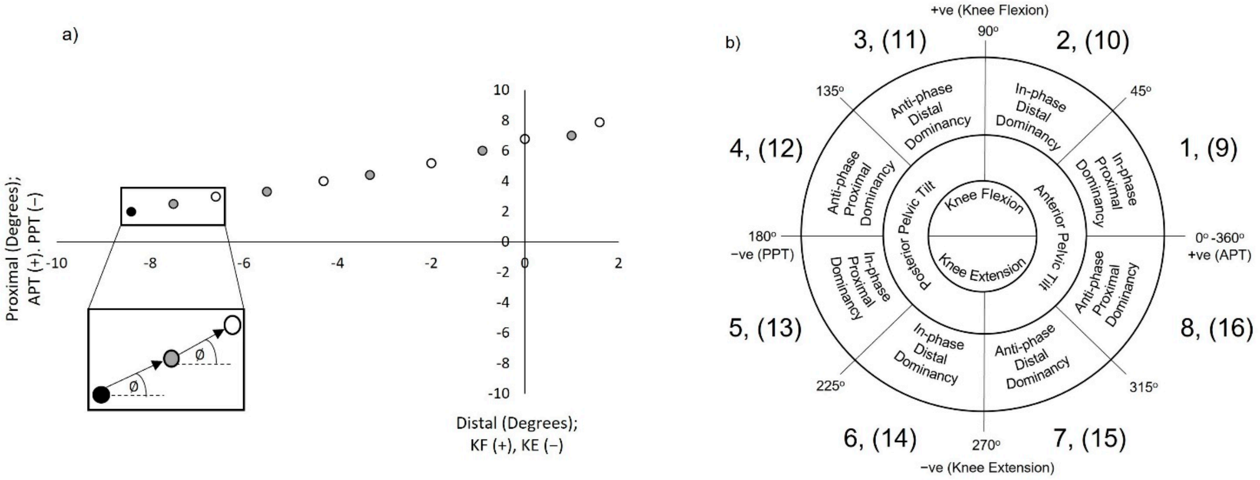

Figure 2. (**a**) Angle-angle plot of pelvic and knee rotations. Black marker represents initial time point. During the consecutive vector coding technique, coupling angles ($\varnothing$) are determined by vector orientation between every two adjacent data points, (e.g., black to grey, then grey to white marker in highlighted). For target-alignment vector coding (TAVC), coupling angle values are determined by vector orientation of data points in respect to initial data point (black marker). Knee flexion (KF); knee extension (KE); posterior pelvic tilt (PPT); anterior pelvic tilt (APT). (**b**) Polar plot permitting categorisation of bins counts of mean coupling angles ($\varnothing_\mathrm{i}$). Numbers 1–8 and 9–16 refer to coordination strategy classifications categorising values of mean coupling angle values ($\overline{\varnothing}_\mathrm{i}$) determined by consecutive and TAVC techniques, respectively.

2.5.2. Establishing Mean Coupling Angles $\overline{\varnothing}_\mathrm{i}$ and Coordination Strategy Classification

Mean coupling angles ($\overline{\varnothing}_i$) were calculated (3–5) using circular statistics to preserve the directionality of data [43] (pp. 30–35). In accord with King and Hannan [39], analysis was performed on the task's descent and ascent phase independently, aiding subsequent interpretation of results. As it was expected that pass and fail groups would differ in their execution of the test (in contrast to employing a single coordination strategy), mean coupling angles ($\overline{\varnothing}_i$) were categorised to eight, 45° width bins for each vector coding technique in accord with the Needham et al. [44] binning convention. Figure 2b displays the eight coordination strategy classifications per vector coding technique (ConVC 1–8, TAVC, 9–16).

2.5.3. Establishing Coordination Variability (CoV)

To inform on Hypothesis 3, CoV was quantified by calculating the angular deviation of pelvis–knee coupling (6, 7) in accord with Needham et al. [38]. Angular deviation represents the circular statistics equivalent of the standard deviation as derived from the arithmetic mean. Appendix A (Figure A1), derived from Fisher [43] illustrates the determination of angular deviation from geometric principles within the unit circle. Vector coding procedures were implemented using Microsoft Excel 2016.

$$\varnothing_{j,i} = tan^{-1}\left(\frac{y_{j,i+1} - y_{j,i}}{x_{j,i+1} - x_{j,i}}\right) \tag{1}$$

$$\varnothing_{j,i} = \left\{ \begin{array}{c} tan^{-1}\left(\frac{y_i}{x_i}\right),\ if\ x_i > 0 \\ 180 + tan^{-1}\left(\frac{y_i}{x_i}\right),\ if\ x_i < 0 \\ 360 + tan^{-1}\left(\frac{y_i}{x_i}\right),\ if\ x_i > 0, y_i < 0 \end{array} \right\} \tag{2}$$

$$\overline{x}_i = \frac{1}{n_j}\sum_{j=1}^{n_j}\left(cos\varnothing_{j,i}\right) \tag{3}$$

$$\overline{y}_i = \frac{1}{n_j}\sum_{j=1}^{n_j}\left(sin\varnothing_{j,i}\right) \tag{4}$$

$$\overline{\varnothing}_i = tan^{-1}\left(\frac{\overline{y_i}}{\overline{x_i}}\right) \tag{5}$$

$$\overline{r}_i = \sqrt{\overline{x}_i^2 + \overline{y}_i^2} \tag{6}$$

$$CoV_i = \sqrt{2\cdot(1-\overline{r}_i)}\cdot\frac{180}{\pi} \tag{7}$$

2.5.4. Target Alignment Vector Coding (TAVC)

Vector coding's ability to quantify relative motion and identify a coupling angle representing optimal test performance, (e.g., 90°) may be expected to see wide adoption of the technique for the investigation of CMCTs. However, only Wilson et al. [11] have employed vector coding during CMCT performance. Additionally, that study represented a single-subject case study design. While it is evident that a more extensive exploration of CMCTs via vector coding is required, the present work also proposes a further refinement to the vector coding technique which is suggested to address a shortcoming of the ConVC technique. As illustrated in Figure 2a, the ConVC technique calculates coupling angles from each adjacent time point for the segments of interest (1). During the initial stages of bilateral partial squat execution, a participant's pelvis may rotate to a position that results in test failure. Yet, if the pelvis remains at this alignment, coupling angle values from this time point forwards may equal either 90° (descent phase) or 270° (ascent phase). As these values represent optimal test performance, such an outcome may mask between-group intersegmental coordination distinctions. Given this shortcoming, an adaptation is presented that is sensitive to tasks possessing a target alignment, (e.g., bilateral partial squat). In contrast to calculating coupling angles from the change in orientation of each consecutive value for the pelvis, 'target alignment vector coding' (TAVC) determines coupling angles with respect to pelvic deviation from the original reference position (Figure 1). By replacing $x_{j,i}$, which represents the denominator of Equation (1), for $x_{j,1}$, coupling angle values for pelvic deviation–knee coupling are derived (8). Only if the pelvis remained at (or returned to) the target alignment would coupling angle values equal 90° or 270°. Therefore, coupling angle mean values and CoV were determined for the novel TAVC technique (2–6, 8).

$$\varnothing_{j,i} = tan^{-1}\left(\frac{y_{j,i+1} - y_{j,i}}{x_{j,i+1} - x_{j,1}}\right) \tag{8}$$

2.6. Statistical Analysis

With respect to Hypothesis 1 (CMCT-fails display greater pelvic deviation during the test), a Hotelling's T^2, a multivariate analysis of variance model comprising only a single independent variable (group) was performed on the following variables (i–iv); participant anthropometric characteristics (i), maximum knee flexion during descent phase (ii), maximum pelvic deviation (iii), and minimum knee flexion during ascent phase (iv).

To inform on Hypothesis 2, an exhaustive chi-squared automatic interaction detection (CHAID; [45,46] algorithm explored whether CMCT-fails displayed greater use of anterior pelvic tilt dominant pelvis–knee intersegmental coordination strategies. For each participant, mean coupling angle values ($\overline{\varnothing}_i$) binned within each coordination strategy classification, were counted. The CHAID algorithm then established whether bin count (predictor variable) was independent of test failure (target variable). If dependence existed (therefore, the null hypothesis was rejected), individual categories of the predictor variable were merged and split via an iterative process of pairwise significance testing (Bonferroni corrected, chi-squared tests). Bins that were most similar (non-significant difference between each category) were aggregated within terminal 'nodes', whilst bins displaying significant differences to others were classified within their own unique terminal nodes [47]. The CHAID algorithm's performance (accuracy) was quantified via *k*-fold cross-validation. A tenfold repeated cross-validation approach was adopted [48]. Supplying insight upon both ConVC and TAVC, the CHAID algorithm was performed separately for each approach. Therefore, the predictor variable possessed eight coordination strategy classifications (bins) for each vector coding technique.

For Hypothesis 3 (CMCT-fails display lower CoV), an SPM variant of an independent *t*-test was performed on intersegmental CoV ($\overline{\varnothing}_i$) waveforms for both vector coding techniques, for the descent and the ascent phase of the test. If waveforms violated normality, non-parametric versions of SPM were applied. Open-source SPM code (www.spm1d.org; accessed on 20 March 2020) was implemented in MATLAB (R2018b; MathWorks Inc., Natick, MA, USA) for all SPM analyses. All statistical analysis was completed using SPSS, version 24 (IBM Corp., Armonk, NY, USA) unless otherwise stated. Significance was set at $p < 0.05$ for all statistical analyses.

3. Results

3.1. Descriptive Statistics

Of the 28 participants tested, 12 were rated as passing the bilateral partial squat; 2 males and 10 females; (38.24 ± 10.42 years, BMI 23.97 ± 3.08). To establish a balanced design, 12 of the participants rated as failing the test were matched on age and BMI. The CMCT-fail group constituted three males and nine females: (37.47 ± 7.01 years, BMI 23.11 ± 2.40). Descriptive statistics for pelvic deviation and knee flexion values (maximum and minimum) are presented in Table 1. Figure 3a,b presents ensemble mean curves for pelvic deviation for both the test's descent and ascent phases, respectively.

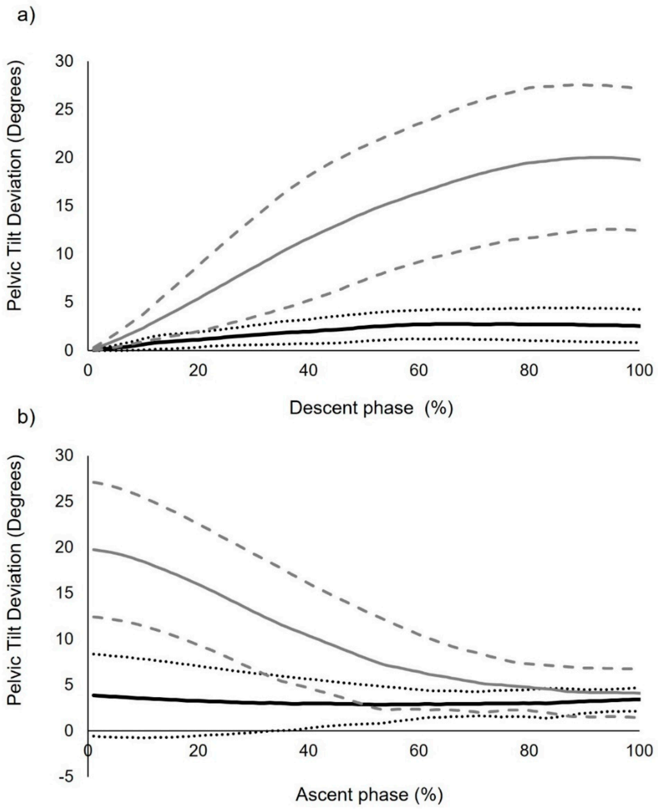

Figure 3. Ensemble curve of pelvic deviation from reference alignment during bilateral partial squat (**a**) descent phase (**b**): ascent phase. Positive values represent anterior pelvic tilt. Black and grey lines represent mean (solid) and SD (dotted) values for pass and fail groups, respectively.

Table 1. Segment and joint rotation maximum (ii, iii) and minimum (iv) values during descent and ascent phase of bilateral partial squat.

Segment and Joint Rotations (Degrees)	Pass (n = 12)	Fail (n = 12)	Mean Difference (95% CI)
Knee flexion at termination of descent phase (ii)	60.84 (6.31)	63.14 (7.18)	2.33 (−0.7–5.3)
Pelvic deviation (iii)	4.08 (1.40)	19.95 ** (6.48)	15.87 (11.9–19.8)
Knee flexion at termination of ascent phase (iv)	3.04 (5.01)	3.10 (4.39)	0.05 (−2.0–2.1)

Note. Confidence intervals' (95% CI) calculation included t-distribution to accommodate small ($n < 30$) sample size. ** indicates significant difference ($p < 0.05$) between the groups.

3.2. Participant Anthropometric/Demographic Characteristics and Segmental Coordination: Inferential Statistics (Discrete and Continuous Analysis)

Preliminary assumption checking revealed the variables of interest (i–iv) as normally distributed (Shapiro–Wilk test, $p > 0.05$) and absent of outliers (boxplot visual inspection). A Hotelling's T^2 analysis was performed with the independent variable of the group (pass or CMCT-fail) and the dependent variables previously identified (i–iv). One dependent variable (iii) failed Levene's test (violated assumption of homogeneity of variances) and was removed from the model. For the remaining variables, Box's M test revealed homogeneity of variance–covariance matrices, ($p = 0.778$) and homogeneity of variances (Levene's test, $p > 0.05$). Hotelling T^2 analysis identified no significant between-group difference on the combined dependent variables (i, ii, iv), $F(4, 19) = 0.229$, $p > 0.05$, Wilks' $\Lambda = 0.954$, partial η^2 =.046. Therefore, in support of the matching process, age and BMI were not statistically different between the groups (Table 1). Additionally, maximum, and minimum values of knee flexion, during the descent and ascent phase, respectively, did not differ between the groups (Table 1). An independent t-test was performed on pelvic deviation during the bilateral partial squat (iii). In violating equality of variances ($p < 0.05$), equal variances were not assumed. There was a statistically significant between-group difference in pelvic deviation (Table 1, $t(12.021) = -7.943$, $p < 0.05$).

3.3. Intersegmental Coordination: Descriptive and Inferential Statistics (Continuous Analysis)

Aggregated mean coupling angle waveforms are presented for ConVC and TAVC in Figure 4 (descent phase) and Figure 5 (ascent phase). Classification tree analysis (exhaustive CHAID) identified bin count derived from both ConVC and TAVC techniques, as a significant predictor variable of bilateral partial squat test failure (Figure 6). For ConVC, individual classifications that achieved between-group significance are identified at nodes a–b, d, and f–h (Figure 5a). Figure 5b identifies individual classifications (nodes i–k, m–n) that achieved between-group significance for TAVC. Model accuracy was identified as 65.8% and 62.8% for ConVC and TAVC, respectively.

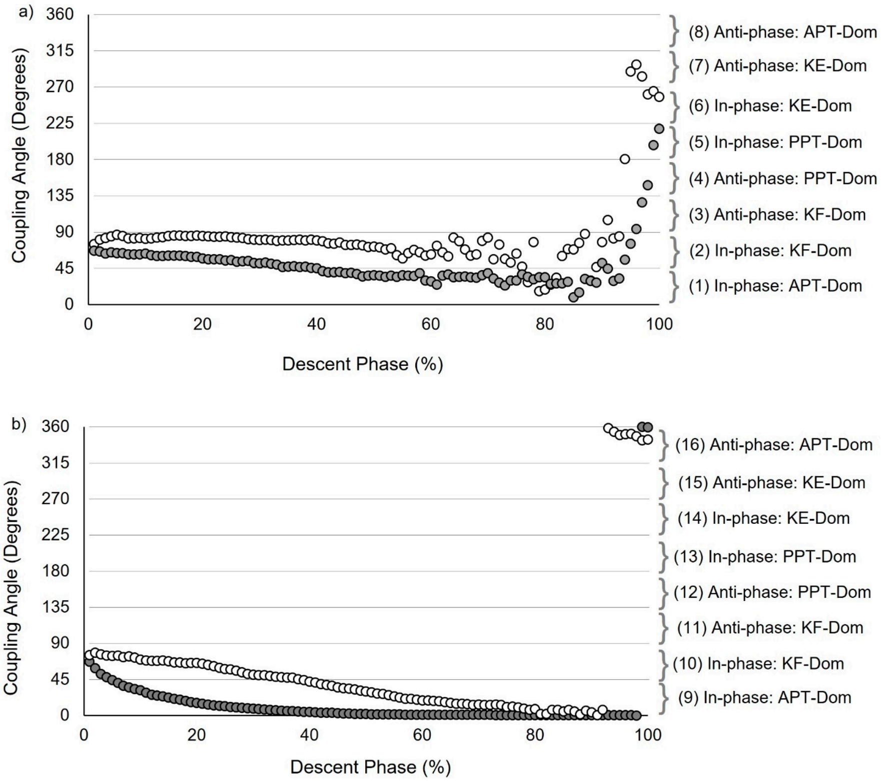

Figure 4. Coupling angle aggregate mean for pelvis and knee coupling during descent phase of bilateral partial squat (**a**) consecutive vector coding; (**b**) target alignment vector coding. White and grey markers identify group mean coupling angles for pass and fail groups, respectively. Dom = dominance.

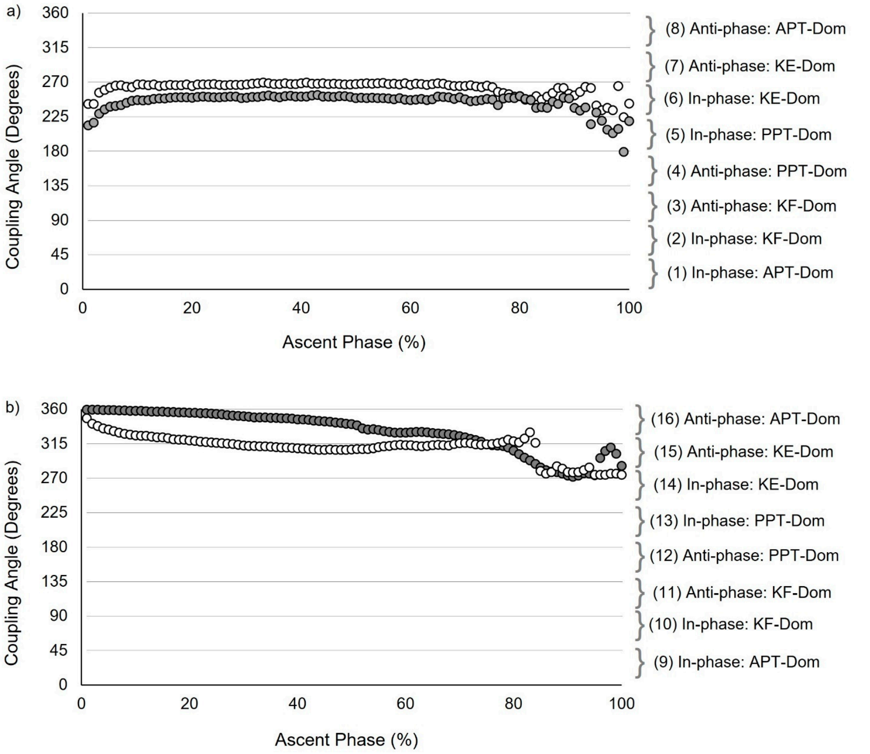

Figure 5. Coupling angle aggregate mean for pelvis and knee coupling during ascent phase of bilateral partial squat (**a**) consecutive vector coding; (**b**) target alignment vector coding. White and grey markers identify group mean coupling angles for pass and fail groups, respectively. Dom = dominance.

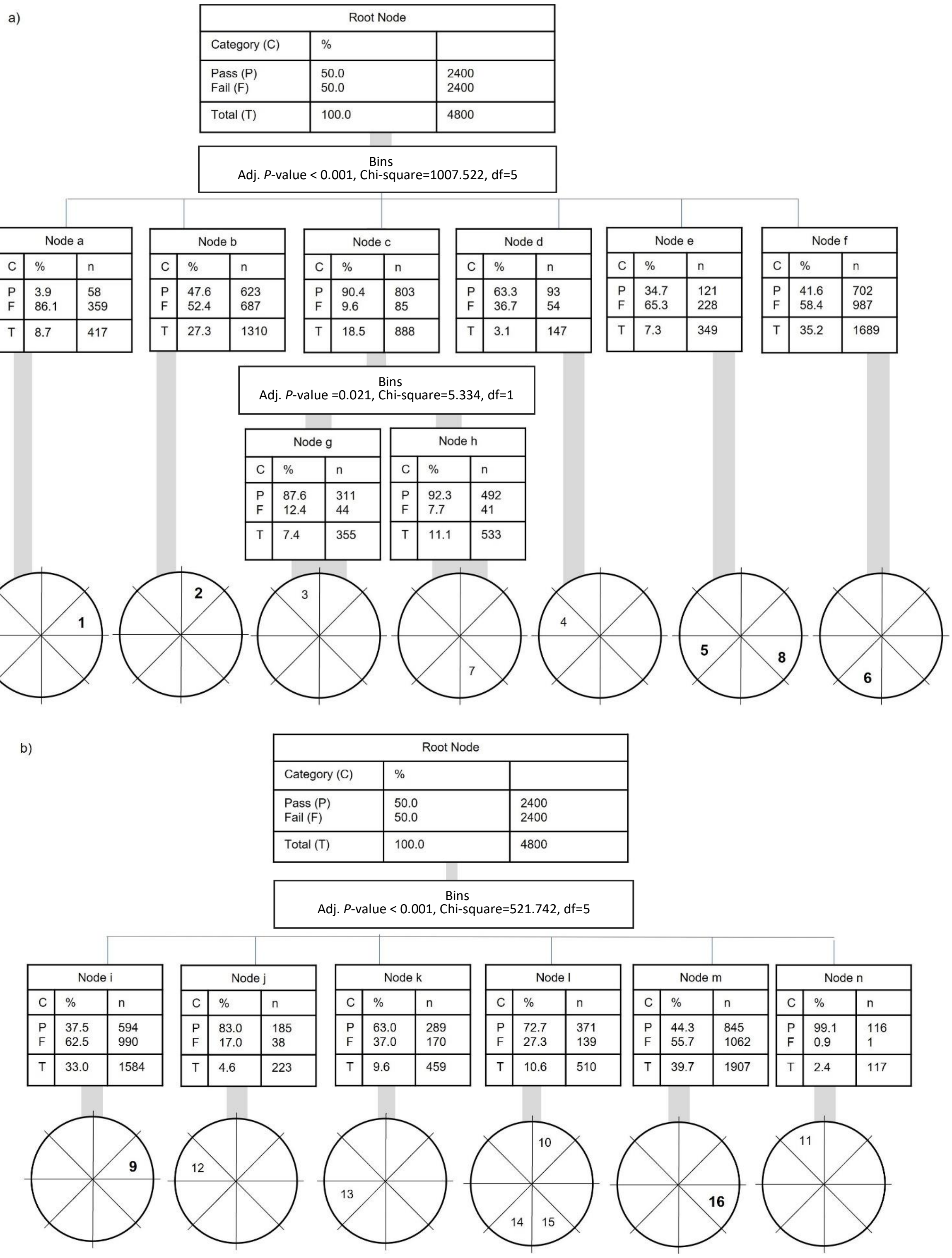

Figure 6. Classification tree results: binned counts of mean coupling angle ($\overline{\varnothing}_i$) to predict failure of bilateral partial squat; (**a**) consecutive vector coding technique. (**b**) target alignment vector coding. Segments within circles represent coordination strategy classifications numbered in accord with Figure 2b. Bold numbers represent classifications in which CMCT-fails displayed greater bin count.

3.4. Inter-Segmental CoV ($\varnothing_i$): Inferential Statistics (Continuous Analysis)

With respect to CoV during the descent phase of the bilateral partial squat, no significant between-group difference was identified for ConVC derived data (Figure 7). In contrast, CMCT fails displayed lower CoV during the descent phase when TAVC derived data were analysed (Figure 8). Mirroring these results, CoV did not differ between the groups during the test's ascent phase for ConVC derived data (Figure 9), whereas CMCT fails displayed lower CoV when TAVC derived data were analysed (Figure 10). Non-parametric SPM variants were applied throughout.

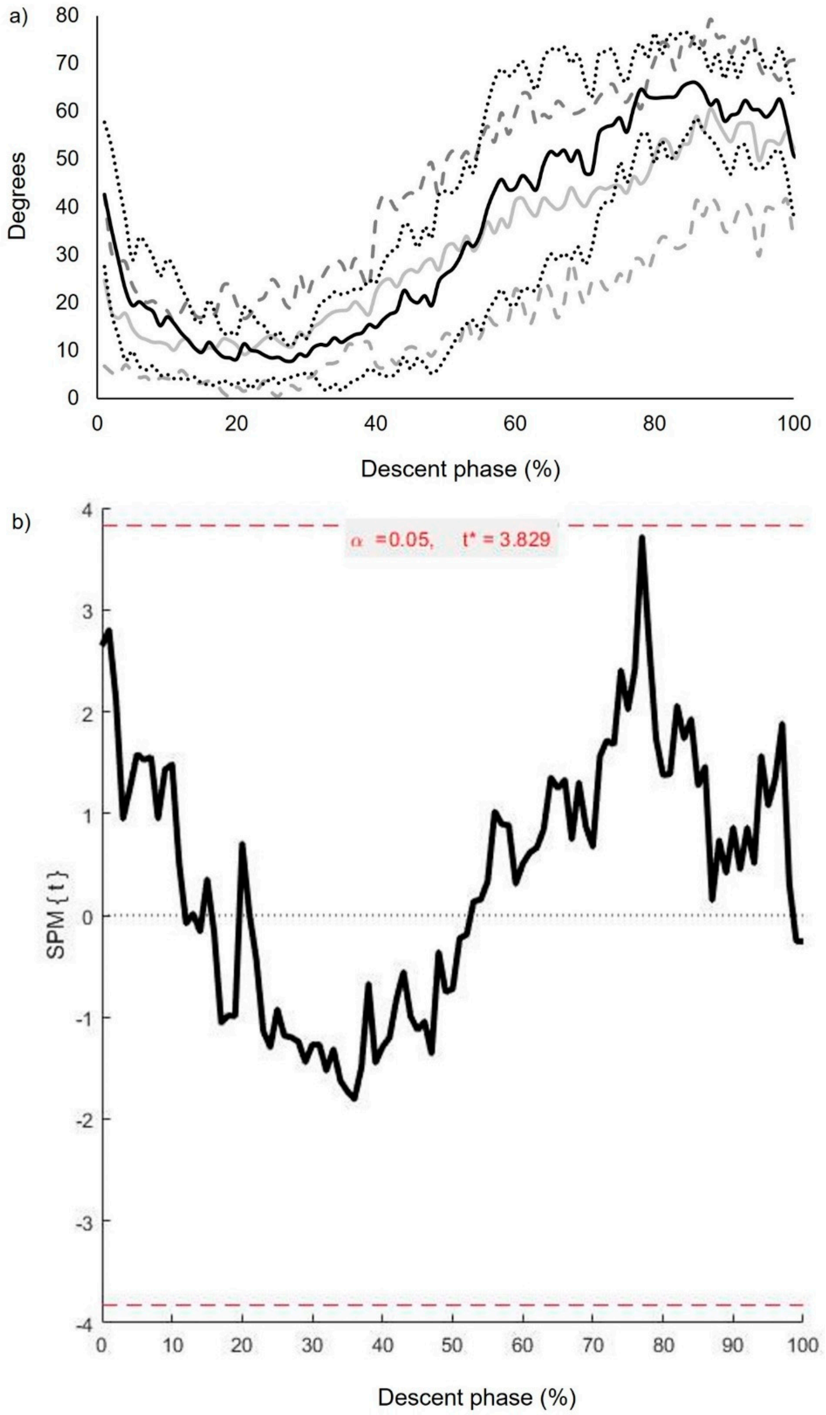

Figure 7. Coupling angle variability ($\overline{\varnothing}_i$) for pelvis and knee (consecutive vector coding): descent phase of bilateral partial squat (**a**) and corresponding spm{t} outputs for between-group comparison (**b**). Note. Figure (**a**); black and grey lines represent means (solid) and SD (dashed) pass and fail groups, respectively. Figure (**b**); SPM{t} critical t-threshold (t*, horizontal dashed line) has not been exceeded indicating no between-group significant difference ($p > 0.05$).

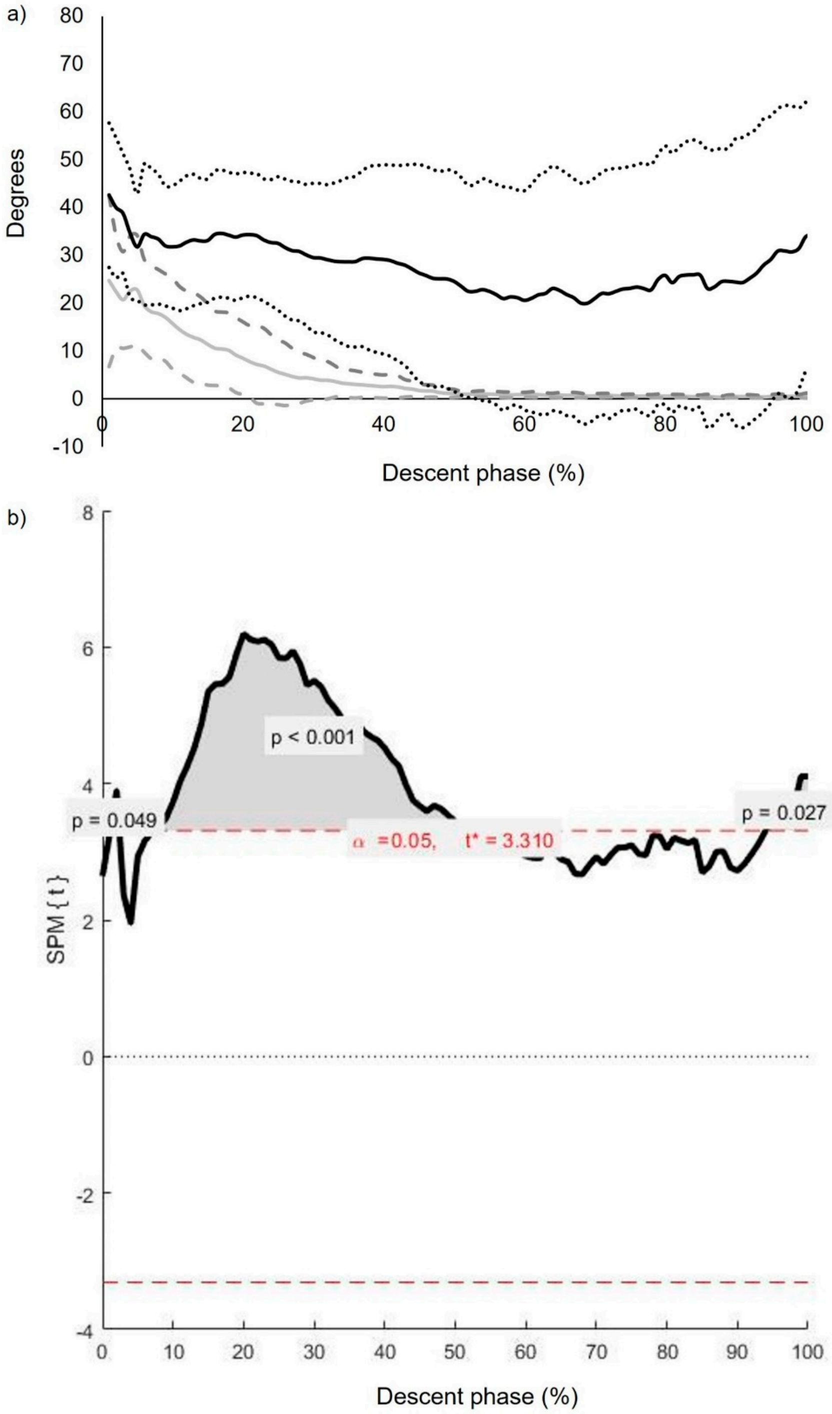

Figure 8. Coupling angle variability $\overline{\varnothing}_i$ for pelvis and knee (target alignment vector coding): descent phase of bilateral partial squat (**a**) and corresponding spm{t} outputs for between-group comparison (**b**). Note. Figure (**a**); black and grey lines represent means (solid) and SD (dashed) pass and fail groups, respectively. Figure (**b**); SPM{t} critical t-threshold (t*, horizontal dashed line) exceeded, indicating a significant between-group difference ($p < 0.05$).

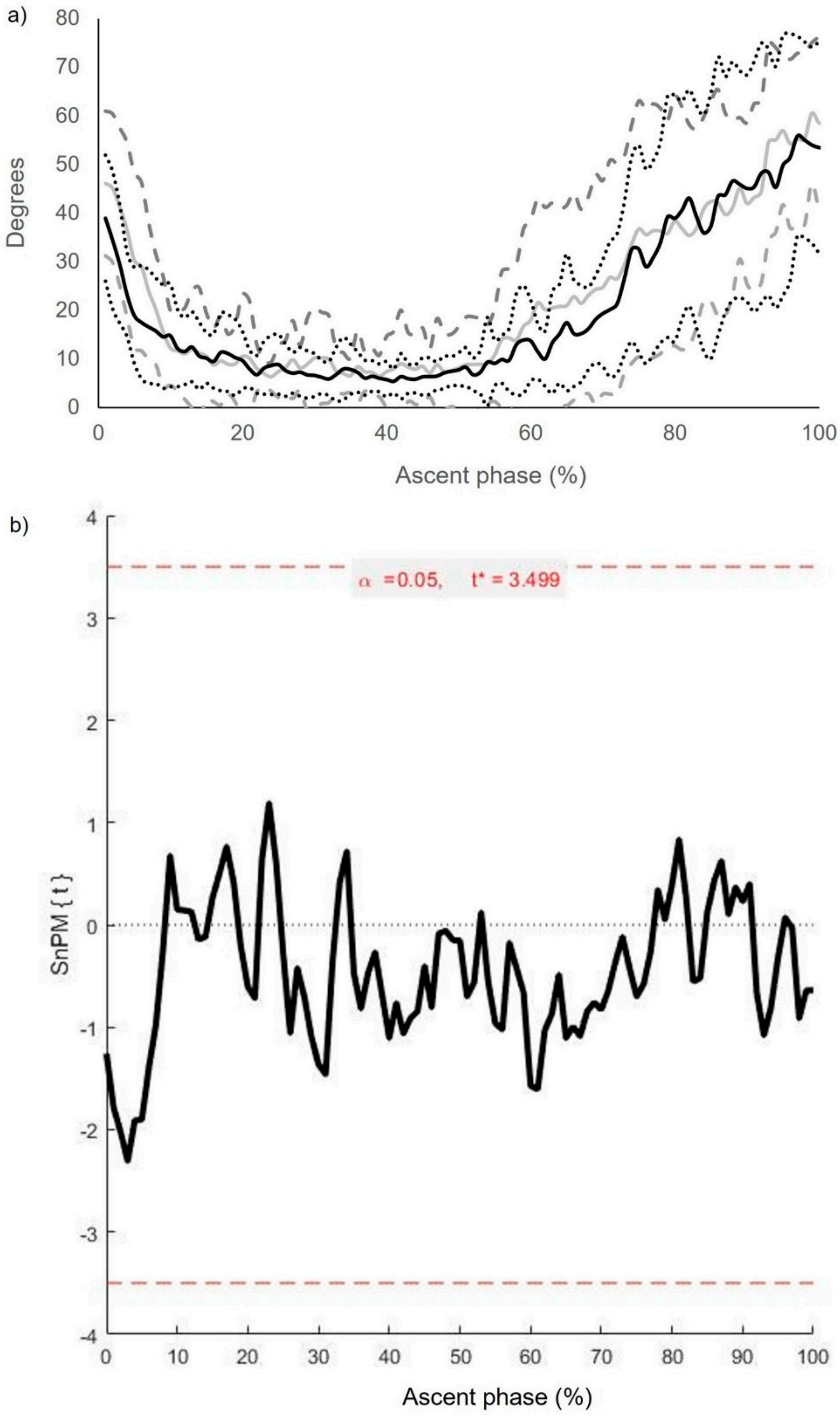

Figure 9. Coupling angle variability $\overline{\varnothing}_i$ for pelvis and knee (consecutive vector coding): ascent phase of bilateral partial squat (**a**) and corresponding spm{t} outputs for between-group comparison (**b**). Note. Figure (**a**); black and grey lines represent means (solid) and SD (dashed) pass and fail groups, respectively. Figure (**b**); SPM{t} critical t-threshold (t*, horizontal dashed line) not exceeded, indicating there is no significant between-group difference ($p > 0.05$).

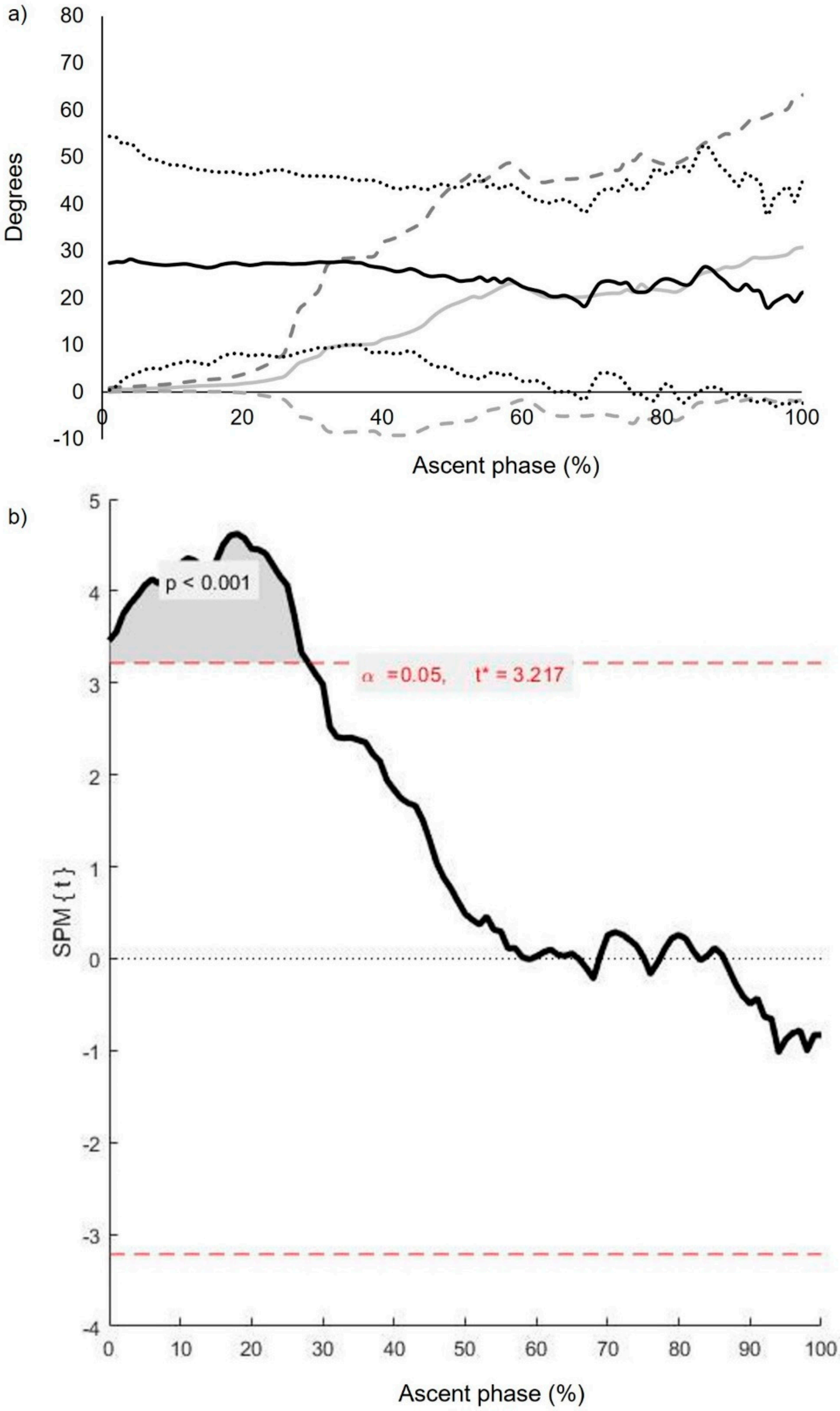

Figure 10. Coupling angle variability $\overline{\varnothing}_i$ for pelvis and knee (target vector coding): ascent phase of bilateral partial squat (**a**) and corresponding spm{t} outputs for comparison between groups (**b**). Note. Figure (**a**); black and grey lines represent means (solid) and SD (dashed) pass and fail groups, respectively. Figure (**b**); SPM{t} critical t-threshold (t*, horizontal dashed line) exceeded, indicating a significant between-group difference ($p < 0.05$).

4. Discussion

Sagittal plane segmental and intersegmental coordination characteristics were explored between participants qualitatively rated as passing and failing the bilateral partial squat, the first testing item of the performance matrix. With respect to Hypothesis 1, CMCT-fails displayed greater pelvic deviation. Considering Hypothesis 2, classification tree analysis revealed bin count derived from both vector coding techniques as a significant predictor of test failure. Specifically, participants failing the bilateral partial squat displayed a greater reliance upon anterior pelvic tilt dominant pelvis and knee coordination strategies. Regarding Hypothesis 3, the novel TAVC technique revealed that CMCT-fails displayed lower CoV. Representing intense scrutiny of the first testing item of the performance matrix, the findings identify CMCT-fails display distinct segmental and intersegmental coordination characteristics, including lower CoV. Results support the qualitative appraisal of CMCT execution at both a segmental and intersegmental level and suggest that reduced CoV accompanies test failure in accordance with the LMC Hypothesis.

One purpose of the study was to consider whether participants qualitatively rated as passing or failing the test displayed distinctions in pelvic kinematics as determined by 3D motion capture technology. With respect to Hypothesis 1, despite considering bilateral in contrast to unilateral squats (as within previous CMCT investigations; [11,34]), a fundamental feature of pelvis segment coordination corresponds between studies; rated as pass or fail, all participants deviated from the target alignment. Highlighting the delineation between tester perception and motion capture technology, the findings support the use of the term 'prevent observable movement' as an appropriate concession to qualitative assessment procedures. The ability to display choice in the execution of a motor task corresponds to descriptions of optimal movement health [49]. The pelvic deviation evident for both groups reinforce the conceptual nature of such a state of volition within expressions of motor behaviour. However, if movement health status is perceived as a continuum, the present findings suggest the pass group is closer to a state of optimality. Table 1 identifies the peak amplitude of pelvic motion representing both the pass and fail conditions as in accord with pelvic kinematics reported in the presence (20.4° ± 3.5°) and perceived absence (post-intervention) of an anterior pelvic tilt deviation (4.8° ± 0.1°) by Wilson et al. [11]. Given the values for the fail condition (5.3° ± 8.6°) reported by Perrott et al. [34], it may be interpreted that testers perceive sagittal plane pelvic deviation greater than approximately five degrees as corresponding to CMCT failure and the presence of LMC.

Considering squat depth, both groups' employment of approximately 60° of knee flexion, illustrates a uniformity of outcome associated with the bilateral partial squat benchmark of ROM (placing the knees five cm beyond the toes). These findings (Table 1) offer some support to the Wilson et al. [11] single leg squat CMCT investigation that proposed placing the knee two cm beyond the toes approximates 50° of knee flexion. However, it is to be acknowledged that benchmarks governed by linear displacement (cm) may be open to criticism due to between-individual distinctions in segment length. Adopting a 60° benchmark, in accord with other contemporary squat task-focused literature [50,51] may limit such concerns, though the clinical expediency of angular versus linear displacement governed benchmarks must be considered. Of note, the Perrott et al. [34] instruction to squat as deep as possible, produced knee flexion values no greater than approximately 50°. Additionally, raising uncertainty regarding benchmark compliance, peak knee flexion values displayed coefficients of variation greater than 20%. The conservative values of Perrott et al. [34] could potentially result in participants attenuating squat depth to increase the likelihood of test success, questioning the utilisation of self-determined benchmarks.

In contrast to the exploration of the segments of interest as discrete entities, both established and novel vector coding techniques permitted quantification of the coordination challenge of the bilateral partial squat at the intersegmental level of analysis (Hypothesis 2). To the authors' knowledge, the present results represent the first statistically interrogated data set derived from vector coding techniques of CMCT execution. Though suggestive of the clinical utility of CMCTs, Wilson et al. [11] reported descriptive statistics only when identifying the percentage of change in intersegmental coordination strategies during single-leg squat execution following an exercise intervention regime with a participant experiencing hip impingement pathology. Within the present work, the between-group distinctions revealed by both vector coding techniques (Figure 6), supply further support for the rater's ability to qualitatively appraise CMCT performance (Hypothesis 2). Additionally, the present results signpost not only future investigations with both clinical and athletic populations in accord with Wilson et al. [11] and Perrott et al. [34], respectively, but also permit consideration of CMCT failure with respect to broader concepts of motor behaviour [2,49,52–54].

Bernstein [52] (pp. 15–59) describes coordination as the mastery of the body's redundant degrees of freedom. Optimal execution of the coordination challenge of the bilateral partial squat, demands knee motion in the absence of pelvic deviation [4,25]. Consideration of ensemble mean curves (Figures 3 and 4), in addition to the array of coordination strategies as classified within Figure 6 renders naïve the assumption of capturing such a display. Yet, the between-group distinctions combined with the divergent outcomes of Hypothesis 1, highlight the need to appraise contrasting abilities to exploit motor redundancy during CMCT execution. Considered with respect to classifications of phase relations and segment dominance, it may be expected that test failure would be characterised by anterior pelvic tilt dominant, in-phase and anti-phase motion, during the bilateral partial squat descent and ascent phases, respectively. Indeed, although the groups displayed an inability to prevent anterior pelvic tilt dominant coordination strategies, both vector coding techniques revealed CMCT-fails' greater appearance within these classifications (Figure 5). With specific respect to ConVC, CMCT-fails' greater appearance within classification 1 corresponds with both the greater peak pelvic deviation observed within Hypothesis 1 and the rater's perception of performance. Indeed, Figure 4a identifies that on the initiation of the bilateral partial squat, CMCT-fails almost immediately gravitated towards anterior pelvic tilt dominant motion, subsequently employing classification 1 at approximately 40% of the descent phase (Figure 5a). Conversely, the pass group displayed a much greater ability to adhere close to coupling angles representing optimal bilateral partial squat execution during both the descent (90°) and ascent (270°) of the task. Flexible employment of coordination strategies is posited as a marker of the health of an individual's motor behaviour, permitting adaptable responses to imposed demands on the system [54]. In accord with Guccione et al. [53], motor behaviour optimality may be more characterised by an ability to access and exploit an array of coordination strategies to 'problem solve' rather than representing a specific technical model of task execution. The present findings identify that despite the highly constrained instructions of the test protocol, pass and fail groups display distinct coordination strategies at both the segmental and intersegmental level. Despite appearing in all classifications, the pass group's greater success in limiting anterior pelvic tilt trajectory motion when questioned is speculated to illustrate an enhanced utilisation of motor redundancy to problem solve even within the constrained demands of the CMCT's challenge.

Proposed to accommodate the CMCT's target alignment criteria, the TAVC technique represents a further novel element within the present work. Comparison of the ensemble mean curves from both techniques (Figures 4 and 5) support TAVC's suggested greater sensitivity to anterior pelvic tilt trajectory deviation. During the descent phase (Figure 4b), TAVC reveals both groups display an anterior pelvic tilt dominant squat (classification 9) circa 45–50% earlier than ConVC. For the ascent phase, Figure 5b illustrates both groups' reliance upon anterior pelvic tilt dominant motion (classification 16). Directly contrasting to the posterior pelvic tilt inclusive classification 6 (Figure 5b), the observed reversal in pelvic trajectories reinforces the difference in emphasis between coupling angles determined by a successive time point technique (ConVC) and those derived from the accumulative deviation of the segment of interest (TAVC). Although both groups are again represented within all classifications, the pass group's greater appearance within six (classifications 10–15) out of eight may again illustrate a more successful employment of motor redundancy to meet the demands of the task (Hypothesis 1). That the two remaining classifications (9, 16) are both anterior pelvic tilt dominant and utilised in greater frequency by CMCT-fails, supports the application of the TAVC technique to delineate the execution of tasks possessing a target alignment such as CMCTs. Though promising with respect to the exploration of CMCTs, it is recommended that TAVC must undergo more extensive scrutiny within subsequent explorations.

With respect to Hypothesis 3, though CoV waveforms derived from the ConVC technique failed to support both this and the LMC Hypothesis, results permit a more direct comparison to existing studies considering bilateral squat tasks [39,55]. In accord with King and Hannan [39], who reported a larger spread of data around mean coupling angle values, the present study saw greater magnitudes of CoV during the descent of the bilateral partial squat compared with the ascent phase. In contrast to King and Hannan's [39] reporting of dispersion around only peak mean values, the present study's ensemble curves permit a qualitative appraisal of the evolution of CoV during both phases. Figures 7 and 9 reveal the rise in CoV accompanying the descent appears not only larger but seemingly occurred sooner (40% onwards) than for the ascent phase (in excess of 60%). Viewed with respect to Hypothesis 1, the increased pelvic deviation accompanying greater knee flexion (Figure 3a), suggests an elevation in task-specific (*can you prevent APT?*) difficulty during the descent phase for both groups. Therefore, the inferred greater and earlier rise in CoV accompanying the task's descent phase may be attributable to this increased demand to meet the CMCT criteria. The work of Maddox et al. [55] supports the notion of increased CoV accompanying increased task demand. Considering ConVC-derived data from bilateral squat execution during varying strength training loading regimes, CoV waveforms appeared to be greater for supramaximal compared to one repetition maximum protocols within ensemble mean curves. However, only the ascent phase was appraised, occluding comparison with the squat's descent within both that and the present study. Additionally, the superincumbent loading employed by Maddox et al. [55] further differentiates that investigation and the motor control demands imposed within the present work. Suggestive that an enhanced search for coordination strategies may accompany changing task demands, the elevated values of CoV seen within the present study at the commencement of both phases (Figures 7 and 9), and the ascent's termination, align with observations of increased angular deviation just prior, or during transitions to new phases of activities [44,56].

The LMC Hypothesis proposes that an inability to prevent segment deviation when requested (LMC) represents reduced CoV [14]. In support of Hypothesis 3, CMCT failure and LMC were accompanied by lower CoV (Figures 8 and 10). However, though garnering support for the LMC Hypothesis these findings were only revealed by the novel TAVC technique. The pass group's greater CoV accompanying precision in task achievement (limiting segment deviation) may appear counter-intuitive, despite supporting Hypothesis 3. However, precision-dependent success in the presence of higher trial-to-trial variability is not novel [57,58]. Experts compared to novices displayed both greater accuracy and trial-to-trial variation in task execution during pistol shooting [57] and playing a musical instrument [58]. The CMCT protocol is posited as a clinic expedient and qualitative tool to inform on CoV [14]. The present findings support the notion that a consistent inability to prevent observable motion occurring during a test of intersegmental coordination (macroscopic low CoV), corresponds to lower kinematically quantified trial-to-trial variability. As lower CoV is associated with clinical presentations [16,17,42] the findings offer one possible explanation for the link between CMCT test failure and subsequent injury occurrence in healthy, athletic populations [20]. Yet this explanation must be contrasted with the literature associating greater CoV with clinical presentations [59–61]. For example, DiCesare et al. [59] identified that in contrast to multi-sport athletes, single-sport athletes displayed greater CoV for hip–knee coupling, which the authors linked to elevated injury risk. A longitudinal study by Desai and Gruber [61] identified runners displaying greater CoV magnitudes as experiencing more injury. That both greater and reduced CoV act as markers of elevated injury risk and represents a confounding feature of the CoV literature. A conceptual compass aiding the navigation of the apparent conflict is presented by Stergiou et al. [62], who propose an optimal window of motor behaviour variability may exist. While falling below the window may elevate overuse injury risk [17], exceedance may reflect compromised proprioceptive abilities, manifesting as a lack of precision in task execution [60], and increasing acute injury risk [59]. Reconciling the LMC Hypothesis with the optimal window proposition is the perspective that while an inability to vary (consistently displaying the same deviation) represents a loss of movement choice (LMC), an inability to show the requested pattern, by consistently displaying varying deviations would also equate to CMCT failure. Unifying both outcomes in the test fail condition is an inability to display the choice to either vary or show consistency [14]. Both scenarios, representing the loss of choice in the execution of a motor task, correspond to compromised movement health [49]. With respect to the present study, contrasting to the CoV magnitudes evident for the pass group during both the descent (Figure 8) and the ascent phase (Figure 10) of the bilateral partial squat, values for the CMCT-fails suggest test failure as residing lower within, or potentially below any conceptual optimal window of variability [62]. The results present support for the LMC Hypothesis; yet, these results are only evident via the pelvis weighted and starting alignment sensitive, TAVC.

While the present study highlighted between-group distinctions in intersegmental coordination characteristics, the reported model accuracy for the classification tree analysis suggests limitations associated with the applied binning methodology. Narrower, more numerous bins would likely alter findings, mandating future determination of binning optimality. Furthermore, despite matching the pass and fail groups on age and BMI, the discrepancy in male versus female participants is acknowledged. This consideration, therefore, acts to signal the need to explore the relationship between age, BMI, and gender on characteristics of coordination in future work. However, it is noted that Takabayashi et al. [56] reported no difference in CoV waveforms when comparing male and female participants via SPM analysis during gait, yet this may not be the case for non-cyclical tasks such as the bilateral partial squat. Although matching the single segment and trajectory focus of the bilateral partial squat, consideration of sagittal plane motion only raises questions as to whether between-group distinctions would be detectable within the frontal and transverse planes, calling for a more comprehensive investigation of the performance matrix and other CMCTs. Indeed, the present study's intense scrutiny of just a single testing item called upon a multitude of analysis techniques. Though tempting to expand the inquiry to consider segment lengths and circumferences, the addition of such features would likely compromise the study's power highlighting the need to increase sample size within subsequent investigations inclusive of a wider array of variables. Finally, the introduction of any novel technique must stimulate the need for rigorous scrutiny. However, subsequent explorations of the TAVC must be considerate of the enforcement of not only the identification of a target alignment at the task's initiation but also of a uniform adherence to a mandatory benchmark of ROM, (e.g., 60° knee flexion). Indeed, as both groups displayed a uniformity of benchmark achievement, the greater weighting given to the pelvis within the TAVC is proposed as supporting this technique's employment within the present study.

5. Conclusions

Kinematic analysis of the bilateral partial squat revealed participants qualitatively rated as failing the test displayed greater pelvic deviation compared to a pass group, as determined by both discrete and continuous analysis. Values greater than five degrees of pelvic segment deviation are perceived as an anterior pelvic tilt LMC. For intersegmental coordination, although both groups utilised a range of coordination strategies, test failure saw greater reliance upon anterior pelvic tilt inclusive in-phase motion as revealed by both novel and established vector coding techniques. The lower CoV identified for CMCT-fails aligns with notions that CMCTs may offer insight on clinically relevant trial-to-trial variability; indeed, reduced CoV accompanied the presence of qualitatively determined LMC. Promising in their support for the LMC Hypothesis, and signposting future investigation of CMCTs and batteries such as the performance matrix, these findings were only evident for the novel TAVC technique.

Author Contributions: Conceptualization, L.B., E.C. and R.M.; methodology, L.B., E.C. and R.M.; formal analysis, L.B.; investigation, L.B.; resources, L.B.; data curation, L.B.; writing—original draft

preparation, L.B.; writing—review and editing, L.B., E.C. and R.M.; visualization, L.B.; supervision, E.C. and R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of ST MARY'S UNIVERISTY, TWICKENHAM, TW1 4SX on the 13 February 2019 (protocol code SMEC_2018-19_61).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data in this study are available on reasonable request to the first author.

Acknowledgments: The authors wish to thank Jack Lineham of St Mary's University, Twickenham, for technical support.

Conflicts of Interest: Lincoln Blandford is an employee of Comera Movement Science who educate and train sports, health, and fitness professionals to better understand, prevent and manage musculoskeletal injury and pain that can impair movement and compromise performance in their patients, players, and clients. The company did not have any influence on the results of the study or the preparation of the manuscript. The remaining authors have no conflicts of interest. No financial support or equities were provided by Comera Movement Science.

Appendix A. Calculation of Coupling Angle Variability (CoV) via Geometric Principles

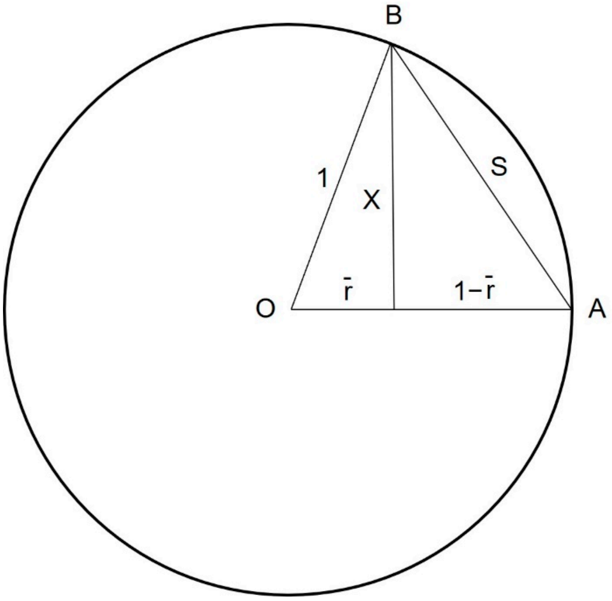

Figure A1. Note. Length S represents angular deviation (CoV). Within the unit circle, lengths OA and $OB = 1$. Therefore, length $OC + CA = 1$. The value $\bar{r}$ is the resultant vector derived from the mean coupling angles at every time point (6) Using Pythagoras, X is identified allowing for the identification of S (7).

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