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Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique

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ABSTRACT

The complexity of human gait patterns has become a topic of major interest in motor control and biomechanics. Range of motion is still the preferred method to quantify movement impairment, however, within these traditional linear measures, the inter-segmental coordination and movement variability is normally ignored. A dynamical systems approach using vector coding and circular statistics provides non-linear techniques to quantify coordination and variability. This study provides comprehensive vector coding and circular statistics calculations. Additionally, pelvis–lumbar coordination and coordination variability data obtained from ten healthy young male participants during five walking trials using an optoelectronic system is provided. This novel data can form the baseline information for future studies in this area of research. Finally, a new illustration to present coordination and coordination variability information of gait kinematics, combining the output from the modified vector coding technique with traditional time-series segmental angle data is presented. This technique, when applied to single patients can be beneficial to assess the effect of an intervention on the patient-specific inter-segmental coordination pattern with implications to clinical setting.

1. Introduction

Q3 Static postural observations and dynamic assessment in a standing position are common examination techniques used by clinicians to determine the severity of spinal dysfunction (Cox et al., 2010). Furthermore, range of motion (ROM) is still the preferred method to quantify impaired movements, with subsequent information used to guide treatment and to assess an individual's progress (Hindle et al., 1990; Intolo et al., 2009). Conventional measures such as ROM do not take into account inter-segmental coordination, movement variability and the different control mechanisms experienced during routine daily activities. From a dynamical systems perspective of motor control, a movement pattern is arranged from constraints imposed from the complex relationships between control parameters; task, organism and environment (Bernstein, 1967; Turvey, 1990). Dynamical system can have implications in assessment of coordination, and Vector Coding (VC) and Continuous Relative Phase (CRP) are common non-linear techniques employed by dynamical system theorists to quantify coordination and variability.

During gait coordination and variability have been linked to the health of biological systems (Harbourne and Stergiou, 2009). Using healthy participants and CRP technique, Lamoth et al. (2002) reported pelvic–trunk coordination is generally in-phase (when the pelvis and trunk are moving in the same direction) at lower walking speeds with transition to anti-phase at higher speeds. In contrast, individuals with chronic low back pain (LBP) have a reduced ability to transfer pelvic–trunk coordination from in-phase to anti-phase as walking speed increases (Lamoth et al., 2006; Selles et al., 2001). Recently using a VC technique, Seay et al. (2011) investigated pelvic–trunk coordination and reported similar findings to studies that employed CRP, indicating that individuals with low back pain (LBP) spent more time in an in-phase relationship as walking speed increases. The authors further concluded that this increase in the in-phase relationship resulted from an increase in pelvis frontal plane ROM. Although the technique utilised to assess coordination and variability should be based on the question asked in the study (Hamill et al., 2012) the use of CRP limits the analysis of coordination to the phase relationship between two segments. On the other hand, vector coding and the proposed four coordination phases (Chang et al., 2008) provides an additional insight to the dominancy of one segment over another and this can offer more valuable information in a clinical setting (Seay et al., 2011). Analysis of coordination variability also reveals important information regarding changes in motor strategies. While there is conflicting evidence to suggest greater variability emerges before the transition from one stable coordination phase to another (Diedrich and Warren, 1995; Haken et al., 1985; Kao et al., 2003; Miller et al., 2010; Seay et al., 2006), recently Miller et al. (2010) associated greater variability with a functional event such as toe-off during gait. However, there is paucity of research regarding coordination and coordination

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variability with other known phases of gait (Perry and Burnfield, 2010; Levine et al., 2012). Therefore, a new illustration combining coordination, coordination variability, ROM and the phases of gait can allow for easier interpretation of the biomechanical data.

Vector coding measures the continuous dynamic interaction between segments by determining the vector orientation between two adjacent data points in time on an angle–angle diagram relative to the right horizontal (Fig. 1b). The outcome measure is referred to as the coupling angle (γ_i) (Fig. 1c) and is represented by a value between 0° and 360° (Sparrow et al., 1987; Hamill et al., 2000). Due to the γ_i being directional in nature circular statistics (Batschelet, 1981; Hamill et al., 2000) are applied to calculate mean γ_i and coordination angle variability (CAV_i) from multiple cycles. Recently it has been proposed the γ_i can be classified into one of four coordination patterns (Chang et al., 2008). Although previous investigations have examined γ_i and CAV_i in healthy and/or pathological groups (Dierks and Davis, 2007; Ferber et al., 2005; Pollard et al., 2005; Pohl and Buckley, 2008; Seay et al., 2011) a lack of clarity in the employed mathematical equations makes between study comparisons difficult and represents possible clinical misinterpretations. This paper aims to (1) present a step by step approach for calculating γ_i and CAV_i (2) provide pelvis–lumbar coordination information during gait in healthy individuals (3) provide new a illustration to present γ_i and CAV_i data.

2. Methodology

Ten male participants (mean ± SD age: 22.4 ± 2.46 years, height: 180.3 ± 7.18 cm, mass: 74.97 ± 11.02 kg) with no history of musculoskeletal impairments gave written consent to participate in the study. Ethical Approval was sought and received from the University Research Ethics Committee.

3. Protocol

Prior to kinematic data collection and to allow familiarisation to the laboratory environment each participant performed walking trials to determine their starting position and preferred walking speed (PWS). Timing gates (Brower Timing Systems, USA) were used during data collection to ensure PWS was achieved. Recording at 100 frames per second, an 8 camera motion capture system (VICON, Oxford, UK) was used to collect pelvis and lumbar segment angular position during five walking trials. Two AMTI-OR6 force platforms (AMTI, USA) collected kinetic data (1000 Hz) to assist in the identification of gait events (heel strike and toe off).

4. Pelvis and lumbar segment coordinate systems

Using double sided adhesive tape reflective markers (14 mm) were attached to the following anatomical landmarks: right and left anterior-superior-iliac spine (ASIS), right and left post-superior-iliac spine (PSIS), sacrum (S1) and spinous process of L1. The lumbar cluster was placed over the spinous process of L3 (Konz et al., 2006).

The global coordinate system (GCS) was defined with the *X*-axis corresponding to the anterio-posterior direction (positive *x*-direction indicated forward progression). The *Y*-axis was defined as medio-lateral direction perpendicular to the *X*-axis parallel to the ground (positive *y*-direction pointing to the left). The *Z*-axis corresponded to the vertical direction (positive *z*-direction pointing upwards). The origin of the pelvis segment coordinate system was the mid-point between the 2 ASIS markers that defined the *Y*-axis. The *X*-axis was directed in an anterior direction perpendicular to the *Y*-axis from the mid-point of the ASIS markers and mid-point between the PSIS markers. The *Z*-axis was formed by the cross product of the *X*- and *Y*-axis. The lumbar coordinate system was defined using the three markers on the rigid cluster (Fig. 2). The *Y*-axis was defined as a line passing through the two markers mounted on the lateral ends of the rigid cluster, with its positive direction to the left. The *Z*-axis was defined from the mid-point of the horizontal markers and the vertical marker with its positive direction aligned with L1. The *X*-axis was the cross product of the *Y*- and *Z*-axis with its positive direction forwards (Needham et al., 2012).

5. Data reduction

Three-dimensional pelvis and lumbar segment kinematic angles relative to the global coordinative system were processed in Visual3D (C-motion-Inc, MD) using a low-pass Butterworth filter with a cut-off frequency of 6 Hz (Winter et al., 1974). Q6 Segment angles were normalised and time scaled to 100% of the gait cycle, from right heel strike to consecutive right heel strike. Angle–angle diagrams were created for all three planes of motion with the proximal oscillator on the horizontal axis and the distal

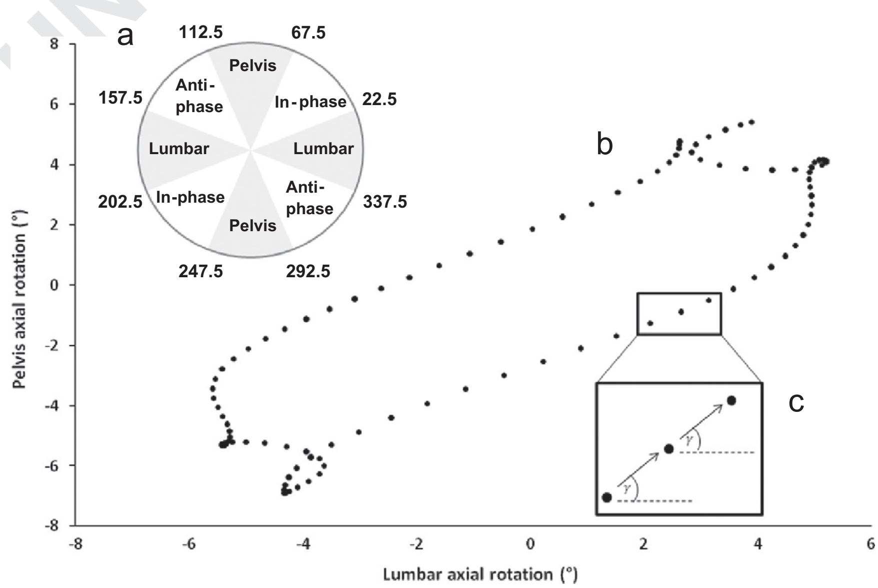

Fig. 1. (a) Classification of coordination pattern from the coupling angle (Chang et al., 2008). (b) Angle–angle diagram of pelvis–lumbar coordination in the transverse plane representing mean data from 10 participants. (c) Coupling angle (γ_i) determined by the vector orientation between two adjacent data points in time on an angle–angle diagram relative to the right horizontal.

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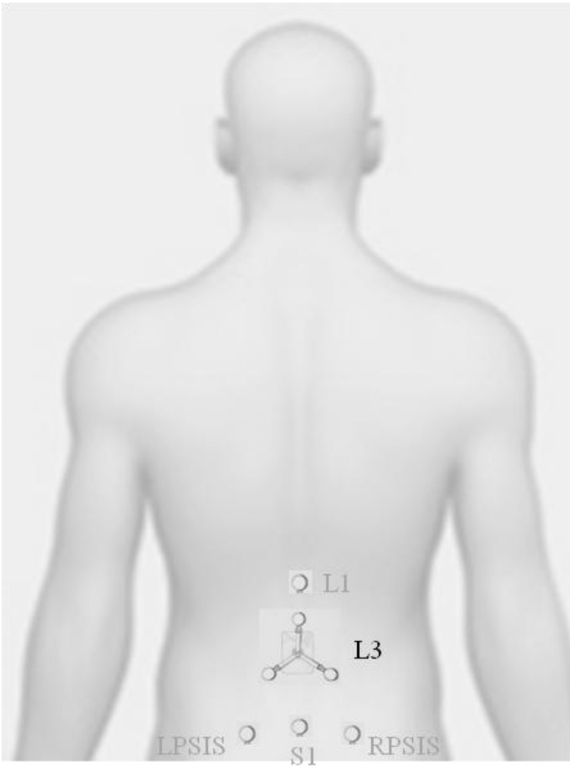

Fig. 2. Marker set configuration.

oscillator on the vertical axis (Fig. 1b). A modified vector coding technique was then employed to quantify inter-segmental coordination. Mean $\bar{\gamma}_i$ and CAV_i for each participant over five trials and across all ten participants were calculated using circular statistics. Mean $\bar{\gamma}_i$ were classified into one of four coordination patterns (Fig. 1a) (Chang et al., 2008). Coupling angle and CAV_i calculations are described in detail below. To assist in the interpretation of the time-series waveforms and coordination patterns, the phases of gait were adapted as IC – Initial Contact, LR – Loading Response, MS – Midstance, PS – PreSwing and Swing phase (Perry and Burnfield, 2010; Levine et al., 2012).

6. Calculation of coupling angle

For each instant (i) during the normalised gait cycle, the coupling angle (γ_i) was calculated based on the consecutive proximal segmental angles ($\theta_{P(i)}$, $\theta_{P(i+1)}$) and consecutive distal segmental angles (θ_D, $\theta_{D(i+1)}$) according to Eqs. (1) and (2):

$$\gamma_i = Atan\left(\frac{\theta_{D(i+1)}-\theta_{Di}}{\theta_{P(i+1)}-\theta_{Pi}}\right).\frac{180}{\pi} \qquad \theta_{P(i+1)}-\theta_{Pi}>0 \tag{1}$$

$$\gamma_i = Atan\left(\frac{\theta_{D(i+1)}-\theta_{Di}}{\theta_{P(i+1)}-\theta_{Pi}}\right).\frac{180}{\pi}+180 \qquad \theta_{P(i+1)}-\theta_{Pi}<0 \tag{2}$$

The following conditions (3) were applied:

$$\gamma_i = \begin{cases} \gamma_i = 90 & \theta_{P(i+1)}-\theta_{Pi}=0 \text{ and } \theta_{D(i+1)}-\theta_{Di}>0 \\ \gamma_i = -90 & \theta_{P(i+1)}-\theta_{Pi}=0 \text{ and } \theta_{D(i+1)}-\theta_{Di}<0 \\ \gamma_i = -180 & \theta_{P(i+1)}-\theta_{Pi}<0 \text{ and } \theta_{D(i+1)}-\theta_{Di}=0 \\ \gamma_i = \text{Undefined} & \theta_{P(i+1)}-\theta_{Pi}=0 \text{ and } \theta_{D(i+1)}-\theta_{Di}=0 \end{cases} \tag{3}$$

Coupling angle (γ_i) was corrected to present a value between 0° and 360° according to (4) (Sparrow et al., 1987; Chang et al., 2008).

$$\gamma_i = \begin{cases} \gamma_i + 360 & \gamma_i < 0 \\ \gamma_i & \gamma_i \geq 0 \end{cases}. \tag{4}$$

7. Averaging and variability calculation

Due to directional nature of coupling angle, the average coupling angle ($\bar{y}_i$) were calculated based on the average horizontal ($\bar{x}_i$) and vertical ($\bar{y}_i$) components at each instant using circular statistics (Batschelet, 1981; Hamill et al., 2000).

$$\bar{x}_i = \frac{1}{n}\sum_{i=1}^{n} \cos \gamma_i \tag{5}$$

$$\bar{y}_i = \frac{1}{n}\sum_{i=1}^{n} \sin \gamma_i \tag{6}$$

The following (7) were applied to correct for the average coupling angle ($\bar{y}_i$) to present a value between 0° and 360°.

$$\bar{y}_i = \begin{cases} Atan\left(\frac{\bar{y}_i}{\bar{x}_i}\right).\frac{180}{\pi} & x_i>0,\ y_i>0 \\ Atan\left(\frac{\bar{y}_i}{\bar{x}_i}\right).\frac{180}{\pi}+180 & x_i<0 \\ Atan\left(\frac{\bar{y}_i}{\bar{x}_i}\right).\frac{180}{\pi}+360 & x_i>0,\ y_i<0 \\ 90 & x_i=0,\ y_i>0 \\ -90 & x_i=0,\ y_i<0 \\ undefined & x_i=0,\ y_i=0 \end{cases} \tag{7}$$

The length of average coupling angle $\bar{y}_i$ was calculated according to (8)

$$\bar{r}_i = \sqrt{\bar{x}_i^{\,2}+\bar{y}_i^{\,2}} \tag{8}$$

Coupling angle variability CAV_i was calculated according to (9)

$$CAV_i = \sqrt{2.(1-\bar{r}_i)}.\frac{180}{\pi}. \tag{9}$$

8. Results

8.1. Illustration description

In Fig. 3a traditional time-series global angular data for the pelvis and lumbar segment in the transverse plane is represented by the black and grey solid lines, with associated axial rotation ROM information on the right vertical axis of the illustration. The $\bar{y}_i$, (black dot) lies within a row that represents the associated coordination pattern (lumbar, pelvis, in-phase, anti-phase) presenting the coordinated relationship between pelvis and lumbar segment global angular data at each time frame during the gait cycle. The $\bar{\gamma}_i$ will also lie within a column that represents a phase of gait. The grey shaded area at the bottom of the illustration represents CAV_i. Both $\bar{\gamma}_i$ and CAV_i outcome measures are quantified in degrees with associated information on the left vertical axis of the illustration.

Fig. 3b represents frequency distribution and coincides with the number of times the $\bar{y}_i$ lies within one of the four coordination patterns during the gait cycle (Chang et al., 2008).

8.2. Pelvis and lumbar segment coordination and coordination variability

Pelvis and lumbar segment coordination in the transverse plane predominantly exhibited in-phase coordination (Fig. 3b) at the end of MS through TS and during mid to late swing phase (Fig. 3a). The high frequency distribution of pelvis coordination (Fig. 3b) is associated

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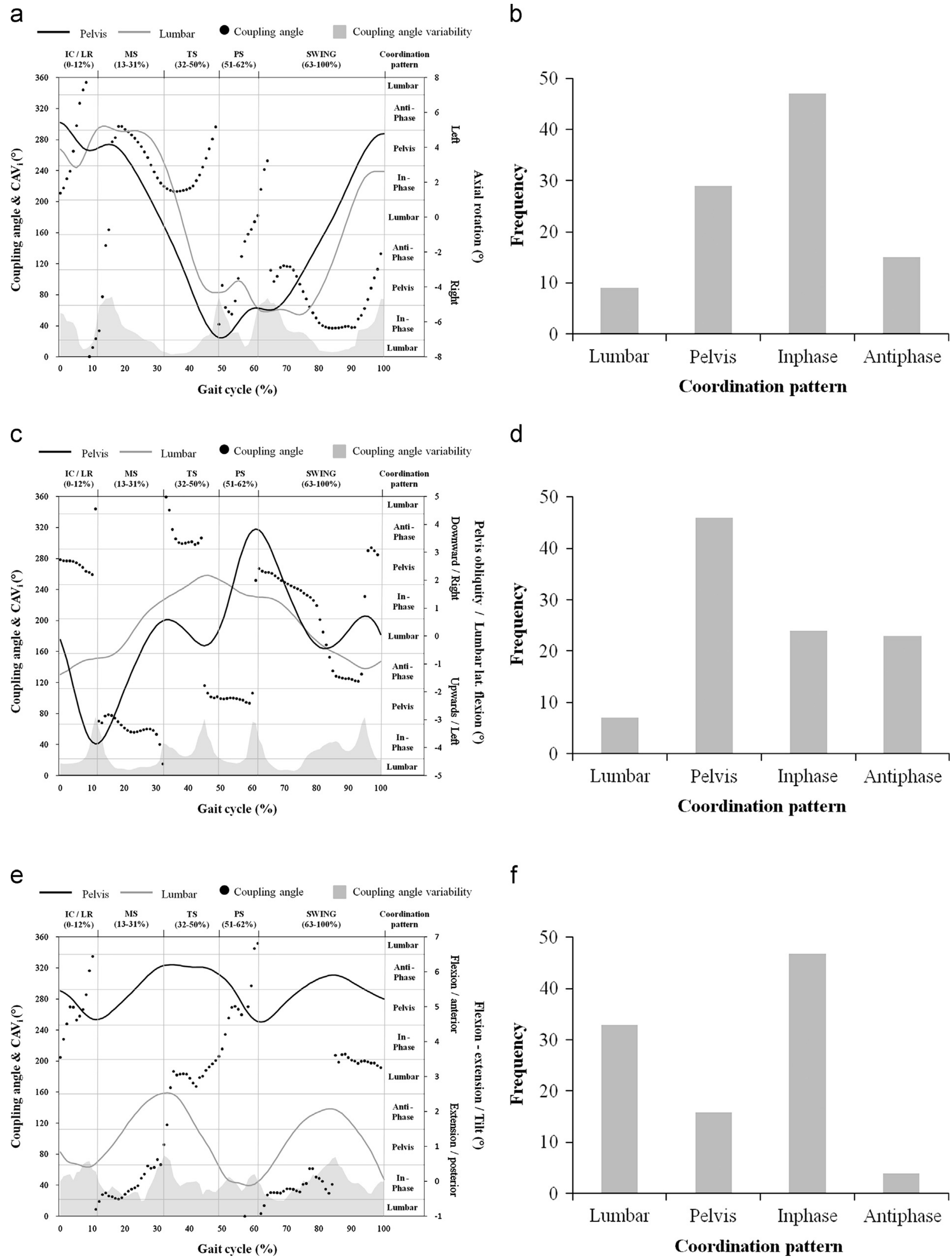

Q9 **Fig. 3.** Mean coupling angle, coupling angle variability (CAV_i) and coordination pattern frequency for pelvis–lumbar coordination in the transverse (a and b), frontal (c and d) and sagittal (e and f) planes.

with the pelvis segment preceding lumbar motion towards the contralateral side during MS and early swing phase while lumbar segment movement remained relatively unchanged (Fig. 3a). High CAV_i between participants was related to changes in coordination patterns with peak variability occurring at the initial stage of each phase of the gait cycle apart from the transition between MS and TS (Fig. 3a).

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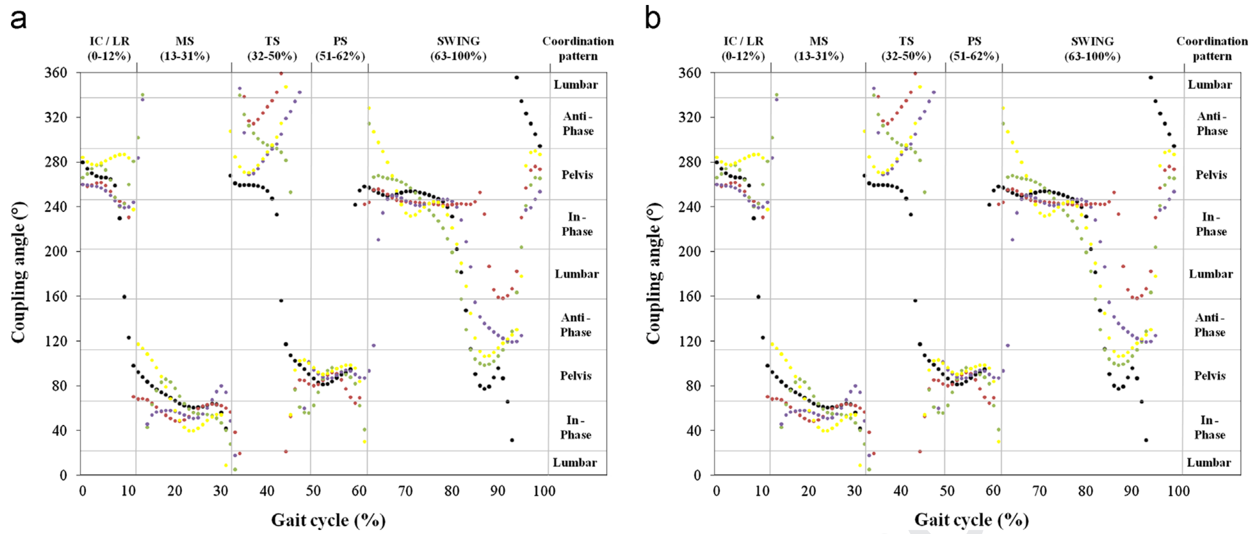

Fig. 4. (a) Mean coupling angle for pelvis–lumbar coordination in the frontal plane for participants 1–5. (b) Mean coupling angle for pelvis–lumbar coordination in the frontal plane for participants 6–10.

In the frontal plane pelvis coordination was predominant (Fig. 3d) during IC/LR, mid to late MS, through PS and during early swing phase (Fig. 3c). This was attributed to greater pelvic ROM as evident from the angular data presented in Fig. 3c. An equal distribution of in-phase and anti-coordination was highlighted (Fig. 3d). High CAV_i was associated with changes in coordination patterns towards the end of LR and PS. High CAV_i during TS and late sing phase was related to a directional change in the movement patterns of the pelvis and lumbar segment (Fig. 3c). Fig. 4a and b highlights the capability of this technique to detect individual differences in a case series analysis.

Pelvis and lumbar segment coordination in the sagittal plane was predominantly in-phase during MS and from early to mid swing phase, with lumbar coordination dominant through TS (Fig. 3f). High CAV_i was associated with changes in coordination patterns towards the end of LR and MS. High CAV_i during the swing phase was related to a directional change in the movement patterns of the pelvis and lumbar segment (Fig. 3e).

9. Discussion

The γ_i is directional in nature and therefore must be reported within a range of 0–360° (Sparrow et al., 1987; Hamill et al., 2000). Subsequently, circular statistics are utilised to provide a mean value from multiple trials (Hamill et al., 2000). However, recent studies have adapted the outcome measure to fall within a range of 0–90° (Ferber et al., 2005; Pollard et al., 2005; Pohl and Buckley, 2008), although a justification for this adjustment was not provided. Constraining the γ_i between 0° and 90° can compress coordination information and may result in a loss of directional sensitivity of movement between two segments (Dubbeldam et al., 2013). Whilst the usability, comprehensibility and the consistency of our approach have not been tested, the vector coding technique and new illustration presented in this paper highlights the reported coupling angle results clearly matches the global data.

Dynamical systems techniques that have employed by investigations to quantify coordination and coordination variability between the pelvis and trunk during gait in healthy individuals and those who suffer from LBP (Lamoth et al., 2006; Seay et al., 2011; Selles et al., 2001). However, these studies modelled the trunk as a single rigid segment which offers little information to the biomechanical influence of LBP on lumbar movement. Quantifying lumbar–pelvis coordination can offer an objective measure of spinal dysfunction and provide an understanding to the underlying mechanisms of a clinical condition (Newman et al., 1996; Cox et al., 2010; Gracovetsky, 2010). Although there is currently no research to compare the results of this study, this paper presents three-dimensional pelvis and lumbar coordination information and the related kinematic variability in healthy young males during gait. This novel data can form the baseline information for future studies in this area and can contribute to research design and sample size calculations for larger clinical trials involving patients with lumbar–pelvic pathologies and other related clinical conditions.

While it is accepted variability is present in all biological systems (Harbourne and Stergiou, 2009) a recent study (Miller et al., 2010) highlighted CAV_i values can be affected by walking speed. Therefore, a number of methodological considerations must be controlled for to ensure no confounding factors influence CAV_i measures. The present study determined the PWS of the participants from 6 un-paced trials over 30-m (Callaghan et al., 1999) and the use of wireless timing gates seemed an appropriate method to control PWS during data collection, However, during learning of a new motor task, variability may be a way to explore and challenge motor strategies (Armour Smith et al., 2011) and due to the sensitivity of CAV_i measures (Miller et al., 2010) more in-depth procedures may be required to ensure participants become familiar with the laboratory and the equipment. For instance, treadmills are commonly used by researchers in clinical gait analysis (Lamoth et al., 2006; Seay et al., 2011; Selles et al., 2001), because of the ease to maintain a constant walking speed. Nevertheless, there is a growing body of literature that suggests there are kinematic differences between over-ground and treadmill walking (Alton et al., 1998; Vogt et al., 2002; Warabi et al., 2005; Chockalingam et al., 2010). While over-ground walking is an everyday activity for most, walking on a treadmill may be a challenging experience for others, i.e. elderly or individuals with pathology. In addition to the above, biomechanical studies often collect data in a single session and/or record a low number of trials (3–5); this potentially increases the likelihood of increased variability which further highlights the importance for familiarisation, particularly when incorporating a dynamical systems analysis. Coordination variability may also be influenced by gender and age of the participant, therefore, further research into the influence of such factors on CAV_i measures is warranted.

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Coupling angle and CAV_i data representing gait kinematics is often presented in a traditional time-series format and reported in separate figures. This approach leads to a lack of detail being presented. If one considers some of the results within the literature, they provide limited information on gait events or phases of gait, making the interpretation of the results difficult. This is particularly complex when the reader is unfamiliar with dynamical systems theory. The present study offered a new illustration (Fig. 3a, c, and e) to present coordination and coordination variability information of gait kinematics, combining the output from the modified vector coding technique with traditional time-series segmental angle data and recognised phases of gait (Perry and Burnfield, 2010; Levine et al., 2012). The advantage of this approach is evident in the results of this study. While $\bar{\gamma}_i$ provides an accurate indication of the coordination pattern (Chang et al., 2008), it does not provide explicit information on the directional movement of the two segments. In Fig. 3c pelvis coordination is dominant during IC/LR and this is due to greater pelvis ROM as outlined by the inclusion of the segmental angular data. Additionally, global angular data revealed an anti-phase relationship between the pelvis and lumbar segment. Fig. 4a and b demonstrates the capability of this technique to identify the individual coordination pattern differences and highlights the importance of single subject analysis. In Fig. 4a for instance, four out of the five participants display pelvis coordination in the frontal plane during IC/LR while only one participant exhibited anti-phase coordination. Without global angular data it is difficult to explain the reason for the anti-phase coordination during IC/LR. The results of this study support the concept that high CAV_i can be associated with the transition between coordination patterns (Diedrich and Warren, 1995; Haken et al., 1985) and corresponds to a functional event during gait such as toe off (Miller et al., 2010). Additionally, this investigation has demonstrated that in healthy young males, high CAV_i can also occur at the beginning of MS, TS, PS and IC, although this is not representative in all planes of movement.

While experimental errors may be instrumental or associated with anatomical landmark identification, it is important to recognise the influence of skin motion artefact which can have affected pelvis and lumbar global angular data in this study. However, ROM data presented in the illustrations (Fig. 3a, c, and e) are consistent with those previous reported (Konz et al., 2006). Pelvis–lumbar coordination and coordination variability data in this study was collected from a small sample size consisting of ten healthy young males. Increased participant numbers are required to further confirm the findings of this study along with the analysis of female and clinical populations.

10. Conclusion

This paper has provided a comprehensive vector coding and circular statistics calculations that allow for a detailed understanding of coordination and coordination variability associated with human movement. The phases of gait included in the data analysis represent a normative range for healthy adults that were applied to the data collected from the healthy young males in this study. In addition, the new illustration clearly highlighted that not all participants displayed the same coordination pattern during the gait cycle, leading to a considerable variation of coordination between individuals. These inter-individual variations represented in this study justify the need for single subject analysis in which a dynamical systems method is combined with the individualised kinematic measures. Furthermore since the coordination patterns can be adversely influenced by pathology, the use of the new illustration provided in this paper when applied to single patients can be beneficial to assess the effect of an intervention on the patient-specific inter-segmental coordination pattern with implications to clinical setting.

Conflict of interest statement

We would like to confirm that this manuscript titled “Quantifying lumbar–pelvis coordination during gait using a modified vector coding technique” has not been submitted elsewhere for full publication and we do not have any commercial conflict of interests.

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