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Adaptations in trunk-pelvis coordination variability in response to fatiguing exercise

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Abstract (289 words)

Background

During walking, variability in how movement is coordinated between body segments from stride to stride facilitates adaptation to changing environmental or task constraints. Magnitude of this inter-segmental coordination variability is reduced in patient populations and may also decrease in response to muscle fatigue. Previously, stride-to-stride variability has been quantified with the Vector Coding (VC) method, however recent research introduced a new Ellipse Area Method (EAM) to avoid statistical artifacts associated with VC.

Research question

Determine changes in trunk-pelvis coordination variability during walking turns in response to fatiguing exercise and to compare coordination variability quantified with VC to the EAM method

Methods

15 young adults (mean age: 23.7 (±3.2) years) performed 15 trials of a 90-degree walking turn before and after fatiguing paraspinal muscle exercise. Angular kinematics of the trunk and pelvis segments in the axial plane were quantified using three-dimensional motion capture. Stride to stride variability of axial coordination between the trunk and pelvis pre- and post-fatigue was calculated using both VC and EAM methods. Magnitudes of pre- and post-fatigue variability for VC and EAM were compared with paired t-tests and relationship between the magnitude of variability for the two methods was calculated using Pearson correlation coefficients.

Results

Using both analytical approaches, trunk-pelvis coordination variability decreased significantly post-fatiguing exercise across the stride cycle and within the stance phase of the turn ($p < 0.034$ for all comparisons). Average magnitudes of variability calculated with VC and EAM were highly correlated. Time series cross correlations pre-post fatigue ranged from 0.81 to 0.98.

Significance

In healthy individuals, magnitude of trunk-pelvis stride-to-stride coordination variability is reduced following fatiguing exercise but the temporal distribution of variability across the stride cycle is maintained. This finding is robust to the method used to quantify coordination variability.

Keywords

Gait, Muscle Fatigue, Paraspinal Muscles, Coordination Variability

1. Introduction

During cyclical movements, healthy motor behavior is characterized by variability across movement repetitions[1]. In particular, the relationship between the extent or direction of movement occurring in multiple degrees of freedom such as body segments varies from repetition to repetition of a cyclical task. This relationship can be quantified as inter-segmental coordination. Variability in patterns of inter-segmental coordination appears to be an important component of successful task performance. An optimal level of coordination variability is associated with skilled, adaptable movement[1].

There are well defined patterns of coordination between the trunk and the pelvis during steady-state gait. Antiphase trunk-pelvis coordination in the axial plane counteracts rotation induced from below by the pelvis and swing limb with increasing step length [2–4]. Stride to stride variability in trunk-pelvis coordination is believed to facilitate dynamic modulation of coordination patterns, and the magnitude of this axial plane coordination variability is reduced in patient populations with impaired neuromuscular control of the trunk-pelvis complex[3]. However, it is not clear how neuromuscular control factors and task constraints interact to produce this altered coordination behavior. In order to understand the role of coordination variability in healthy and disordered movement, it is necessary to first investigate how healthy individuals modulate movement variability in response to changing task or neuromuscular constraints.

One neuromuscular factor that may influence trunk-pelvis coordination variability is trunk muscle fatigue. Studies indicate that inter-segmental coordination and coordination variability are modulated in order to maintain the successful performance of cyclical tasks following fatiguing exercise[5]. The extent and direction of changes in variability post-fatigue appear to be dependent upon the characteristics of the task, and the role of the fatigued musculature in the performance of the task[5,6]. During sidestep cutting the magnitude of inter-joint coordination variability in the lower limbs decreases following localized fatigue of the hamstring musculature[7], and hip-knee coordination variability also decreases during sprinting in response to fatigue[8]. In these studies, fatigue was induced in the muscles responsible for propulsion during running gait. However, the trunk musculature maintains posture rather than providing propulsion during walking, and to date it is unknown how trunk muscle fatigue influences trunk-pelvis coordination variability during gait.

Gait is frequently perturbed from the steady-state by deviations or reorientations in the line of progression that are made to avoid environmental obstacles or to change direction of progression. Walking turns are an ideal gait perturbation to investigate coordination variability as the change in body orientation during turning requires a modulation of trunk-pelvis coordination to maximize stability. In particular, turns that occur ipsilateral to the

stance limb, sometimes termed ipsilateral pivot turns or spin turns, are associated with rapid and complex changes in trunk-pelvis coordination[9]. Therefore, the ipsilateral walking turn paradigm may be more helpful to elucidate changes in coordination variability in response to fatigue in healthy individuals than analyses of steady-state gait.

There are multiple computational approaches for quantifying inter-segmental coordination variability during gait. One of the most commonly used is the vector coding method, which is based upon angle-angle plots of relative motion(VC,[10]). However, estimates of coordination variability made using VC may be artificially inflated in during time-periods when segmental motion is small. Recently, Stock et al., proposed a novel ellipse area method (EAM). EAM provides variability estimates that are robust to the extent of segmental motion as it characterizes variability in both direction and amount of relative motion[11]. To date there has been no direct comparison utilizing VC and EAM to calculate magnitude of coordination variability during human movement.

The purpose of this study therefore was a) to measure change in trunk-pelvis coordination variability during walking turns in response to fatiguing exercise; and b) to compare coordination variability quantified with VC to the novel EAM method. We hypothesized that inter-segmental coordination variability would be reduced in healthy individuals following fatigue.

2. Methods

2.1 Participants

Fifteen healthy adults participated (nine females; mean age 23.7 ± 3.2 years; height 170.1 ± 7.7 cm; mass 65.0 ±11.7 kg). Individuals were aged between 18 and 40, with no history of back pain requiring modification of activity or medical care, and no current lower limb injury affecting locomotion. The sample size was determined by power analysis from our previous work indicating a sample size of 10 would be required to detect altered coordination variability with an alpha of 0.05, beta of 0.80 and effect size of 0.9[12]. Thirteen of the participants were right-leg dominant.

2.2 Instrumentation

Kinematics were quantified using a 10-camera motion capture system (250Hz, Motion Analysis Corporation, Rohnert Park, USA). Rigid kinematic models of the pelvis and trunk were defined and tracked using 14mm retro-reflective markers. A local coordinate system for the pelvis was defined during a static calibration trial using markers on the iliac crests and on the L5/S1 disc space and motion was tracked with the same markers[13]. The

coordinate system for trunk was defined by a rigid triad of markers over the spinous process of T3 and motion was tracked with T3 markers and markers on the acromioclavicular joints and spinous process of C7[9,14]

2.3 Experimental task

Participants walked along a 7-meter walkway. On a force plate embedded in the ground in the center of the walkway, participants made a 90° turn toward the side of their dominant leg before continuing to walk in the new line of progression. Participants initiated the turn with the foot ipsilateral to the turn direction and completed the turn by the end of a single stride cycle (Figure 1). Average walking velocity was controlled at 1.5m/s ± 0.075m/s[9,12]. This is slightly faster than self-selected turning speed in young adults and helps to ensure a consistent ipsilateral pivot strategy for the turn[15]. Participants practiced the turning task until they were able to consistently achieve the correct foot placement and gait velocity and then 15 turning trials were collected.

2.4 Fatiguing protocol

The paradigm utilized for fatiguing the paraspinal musculature was the maximal endurance Sorensen test. This paradigm has been widely reported and validated elsewhere[16,17]. Participants lay prone on an examination table with the lower limbs supported, the anterior superior iliac crests aligned with the edge of the table, and the upper trunk unsupported. The pelvis and lower limbs were stabilized to the table using cushioned straps. Participants were asked to maintain a horizontal body position with the arms crossed across the chest for as long as possible. Standardized verbal encouragement was provided while the hold time was measured with a stopwatch. The test was terminated when the participant was no longer able to maintain the horizontal test position, or when they voluntarily stopped the test due to fatigue. Assessment of failure to hold the test position was standardized by observation of a plumb bob hung around the participant's neck, with sustained motion of more than 1 inch downwards indicating the end of the test[18]. Immediately after completing the fatiguing protocol, participants repeated the turning trials exactly as previously described. To determine if muscle pain or discomfort might confound the effect of fatigue on coordination variability, participants completed two visual analogue scales (VAS) for pain in the paraspinal region. The VAS ranged from 0 (no pain) to 100mm (maximal possible pain). The VAS were completed for a) pain experienced during the fatiguing exercise and b) pain experienced during the post-fatigue walking turns. EMG data were collected from the lumbar paraspinal musculature during the Sorensen test. Further details of the EMG methodology and analysis of EMG median frequency indicating muscle fatigue are included in the supplementary materials.

2.5 Data processing

The turn stride cycle was subdivided into stance and swing phases. The beginning and end of the stance phase of the turning limb were determined from the onset and offset of vertical ground reaction forces (threshold of 20N) and the second initial contact of the turning limb was determined from a local minima in the vertical trajectory of a triad of markers placed on the heel.

Kinematic data were low-pass filtered with a zero-lag, cut-off frequency of 10Hz, 4th order Butterworth filter [9,12]. Axial plane pelvic and trunk segment rotation were calculated across the turn stride cycle relative to the global coordinate system using Cardan angles with a rotation order of XYZ (flexion/extension; abduction/adduction; axial rotation)[19]. Trials where marker occlusion occurred were excluded, but for all participants there were at least 11 walking turns suitable for analysis for both conditions[20]. The number of turns analyzed for pre- and post-fatigue was the same for each participant. Data were then exported to MATLAB® for VC and EAM analyses (MathWorks, Natick, USA).

2.5.1 Vector coding method analyses

The VC method has been described elsewhere[20] and additional details are provided in the supplementary material. Briefly, for each interval in a time series, a coupling angle is calculated. The coupling angle can be represented graphically as the angle from the right horizontal of a vector connecting successive data points on the trunk-pelvis angle-angle plot (Figure 2a and b). Across multiple trials, the variability of the coupling angle at each time interval is quantified as the angular deviation using circular statistics[20]. The average angular deviation was calculated across the stride cycle, and for the stance and swing phases. Larger angular deviation indicates greater variability. We have previously established the test-retest reliability of this method for quantifying trunk-pelvis coordination variability and demonstrated a standard error of measurement of 0.23° [9], and therefore a minimal detectable change value of 0.64°.

2.5.2 Ellipse area method analysis

The EAM approach has also been detailed elsewhere[11] and additional details are provided in the supplementary material. Like VC, this method can be visualized as a series of vectors connecting successive data points of trunk-pelvis motion across the stride cycle of the turn (Figure 2a and c). The variability of the direction and length of these vectors at each time point across multiple trials is quantified as the area of an ellipse encompassing the data points from all trials at that time point with 95% probability. The length of the axes of the ellipse are calculated from the eigenvalues of the trunk-pelvis excursion covariance matrix, and 95% probability is calculated using a Chi-Squared function. The average ellipse area was calculated across the stride cycle, and for the stance and swing phases. Larger ellipse area indicates greater variability.

2.6 Statistical analyses

Data were checked for normality of distribution. Paired t-tests were used to compare the magnitude of pre- and post-fatigue variability for VC and EAM for the entire stride cycle and for the stance swing phases of the turn. Effect sizes (ES) for paired t-tests were calculated. Similarity between the variability time-series before and after fatigue for each method was quantified with cross-correlation at zero lag time[21]. The linear relationship between the magnitude of variability for the two methods was calculated for the stride cycle and stance/swing phases using Pearson correlation coefficients.

3. Results

Average duration of hold for the Sorensen test was 107 ± 48s. Participants reported 33.7 ± 23.5mm pain during the fatiguing exercise. This reduced to 4.9 ± 7.5mm pain during the walking turns post-fatigue. All participants were able to maintain the target walking speed pre- and post-fatigue. Average duration of the turn stride cycle was 1.08 ± 0.09s pre-fatigue and 1.05 ± 0.07s post-fatigue. The duration of the stance phase of the turn did not differ across conditions (63.60 ± 1.76% of the stride cycle pre-fatigue and 63.07 ± 1.79% post-fatigue exercise, $p = 0.135$).

3.1 Change in trunk-pelvis coordination, quantified with vector coding

The time series of VC coordination variability averaged across the group for the stride cycle of the turn pre- and post-fatigue is shown in Figure 3a. VC coordination variability decreased significantly post-fatiguing exercise across the stride cycle and separately for both the stance phase and the swing phase of the turn (Figure 4a, Table 1). For all individuals there was a high cross-correlation between the pre- and post-fatigue time series (median correlation coefficient 0.93, range 0.90 – 0.99, Figure 4c).

3.2 Change in trunk-pelvis coordination, quantified with ellipse area method

The time series of EAM coordination variability averaged across the group for the stride cycle of the turn pre- and post-fatigue is shown in Figure 3b. EAM coordination variability decreased significantly post-fatigue across the stride cycle and for the stance phase but did not change significantly during the swing phase of the turn (Figure 4b, Table 1). For all individuals there was a high cross-correlation between the pre- and post-fatigue time series (median 0.92, range 0.81 – 0.98, Figure 4c).

3.3 Relationship between VC and EAM analyses

There was a significant linear correlation between the average magnitude of variability measured with VC and EAM during the stride cycle and stance phase pre-fatigue, and between VC and EAM results for the stride cycle, stance and swing phases post-fatigue (Table 2).

4. Discussion

This study demonstrates that fatigue influences trunk/pelvis coordination variability during walking turns. This study is also one of the first to explore coordination variability using two different non-linear variability analyses. We demonstrate that use of VC or EAM to quantify variability does not influence the findings for average magnitude of variability across the stride cycle. However, there are some differences in the temporal distribution of variability.

During walking at moderate to fast speeds, trunk-pelvis axial plane inter-segmental coordination is predominantly antiphase[2,3]. For walking turns this antiphase inter-segmental coordination is modulated to realign the body in the new line of progression and then rapidly transition back to the steady-state cycle[9]. From stride to stride, variability in the pattern of inter-segmental coordination may provide a mechanism to compensate for movement errors due to neuromuscular noise and stride to stride perturbations that occur even during steady-state walking. Decreased trunk-pelvis coordination variability is evident in individuals with impaired neuromuscular control of the trunk, including patients with Parkinson's Disease and with persistent low back pain[3,22,23]. Conversely, increased inter-segmental coordination variability may be reflective of unskilled or unanticipated movement[1,22]. It is not clear how large a change in coordination variability is biomechanically or clinically significant. In these healthy participants successful task performance, quantified as walking velocity and duration of the stride cycle, was maintained post-fatigue despite decreased variability. However, it is important to note that the change in VC variability associated with fatigue in this study far exceeded the minimal detectable change value calculated from our previous reliability study[9].

The time-series comparisons in this study demonstrate that although magnitude of variability decreases in response to fatigue, the temporal structure of variability associated with the task is retained. To our knowledge, this is the first report of altered coordination variability during walking or turning in response to paraspinal muscle fatigue. In this study we did not determine the mechanism underlying fatigue-induced changes in kinematics. However, muscle fatigue is associated with impaired proprioceptive and cutaneous sensory function as well as altered peripheral muscle performance[25]. Previous research investigating the influence of fatigue on neuromuscular control of the trunk demonstrated that localized muscle fatigue results in central reorganization of neuromuscular strategies[26]. This reorganization encompasses both fatigued and non-fatigued muscles and

is characterized in part by increases in co-contraction[27]. Greater co-contraction within the dorsal and ventral trunk musculature may be a strategy to increase trunk-pelvis stiffness and minimize the effect of force fluctuations in fatigued muscles[28]. The compensatory trunk-pelvis stiffness also appears to modulate patterns of axial coordination between the segments[29] and greater trunk-pelvis stiffness has been reported in patients with reduced coordination variability[30].

Our study demonstrates that average magnitude of coordination variability was reduced following fatiguing exercise and that this finding was independent of the method used to quantify variability. In addition, magnitudes of variability measured with VC and EAM were highly correlated. To date only one other study has directly compared results from VC and EAM analyses[11]. Stock et al. noted some similarity between the VC and EAM variability time-series of hip/knee sagittal plane variability during running in a single participant. We found that VC coordination variability was greatest at the end of stance and during the swing phase of the walking turn, whereas EAM variability peaked during stance phase. These differences are likely due to the sensitivity of VC to vector length, as previously reported[11], as well as fundamental differences between the two methods in the way that variability that is quantified. EAM measures variability in both the orientation and excursion of relative motion between segments whereas VC solely quantifies variability in orientation. The amplitude of axial plane excursion for the trunk and pelvis, and therefore the vector lengths at each time point, are greater during the stance phase of walking turns than the swing phase[9], resulting in the potential for greater variability during stance phase when measured with EAM. In contrast variability quantified with VC is greatest when smaller amplitude of motion at each time point is accompanied by high stride-to-stride variability in segmental orientation, for example around deflection points during the stride cycle when the direction of axial rotation changes[3].

Our findings suggest that it may be prudent to utilize more than one method to characterize inter-segmental coordination variability during walking. Method selection should be considered carefully from the perspective of motion excursion and whether the research hypothesis involves magnitude of variability during sub-phases within the gait cycle or the temporal distribution of variability. If the research hypotheses include pattern of coordination as well as coordination variability, then the VC method has the advantage of providing clinically interpretable inter-segmental coordination patterns from segmental position data.

There were some limitations to the study. As with all research utilizing voluntary fatiguing protocols, the duration of the Sorensen test, and therefore the extent of fatigue, is to some extent dependent upon participant motivation. However, the Sorensen protocol has been widely used and validated and average hold time in this study is consistent with that reported in healthy individuals elsewhere[16].

Conclusion

In healthy individuals, magnitude of trunk-pelvis stride-to-stride coordination variability decreases following fatiguing exercise while the temporal distribution of variability across the stride cycle is maintained. This may reflect a strategy to reduce degrees of freedom in response to fatigue-induced motor and sensory impairments. This finding is not affected by the method used to quantify coordination variability.

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Conflict of interest statement:

None to declare.

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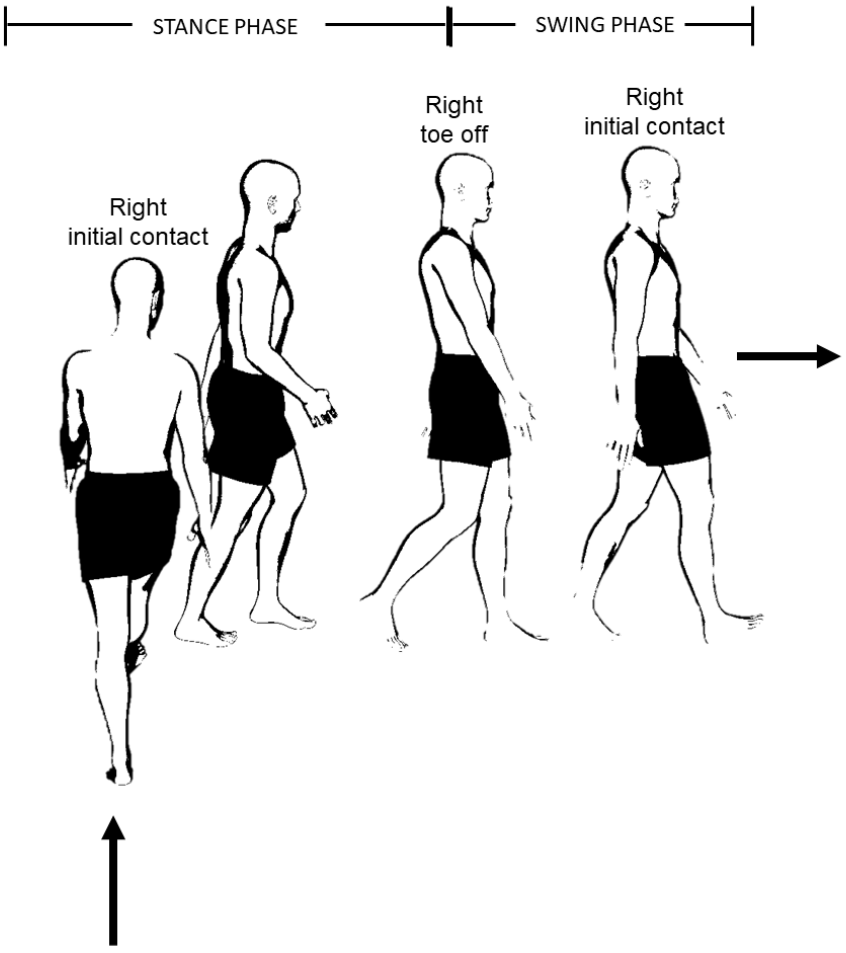
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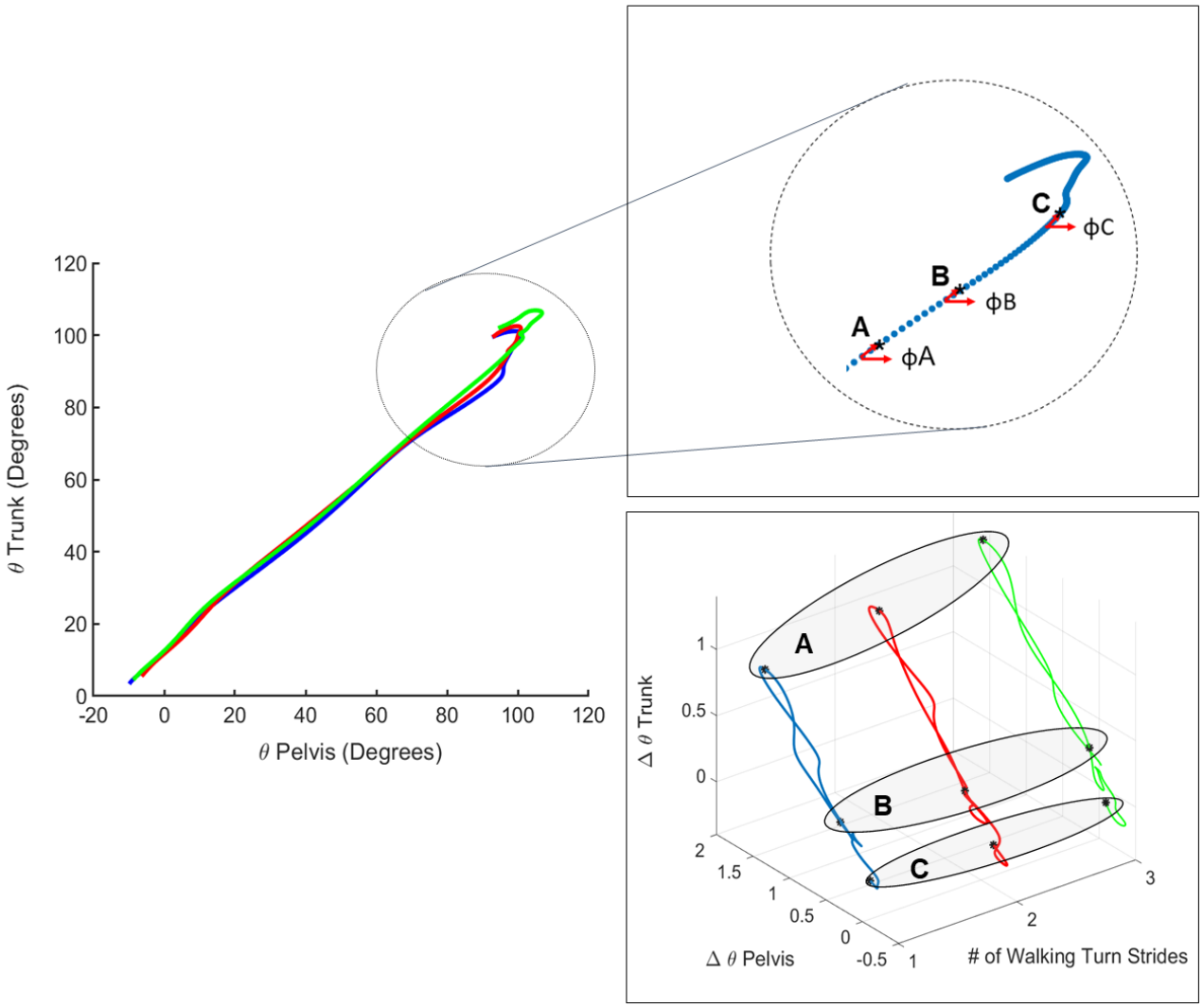
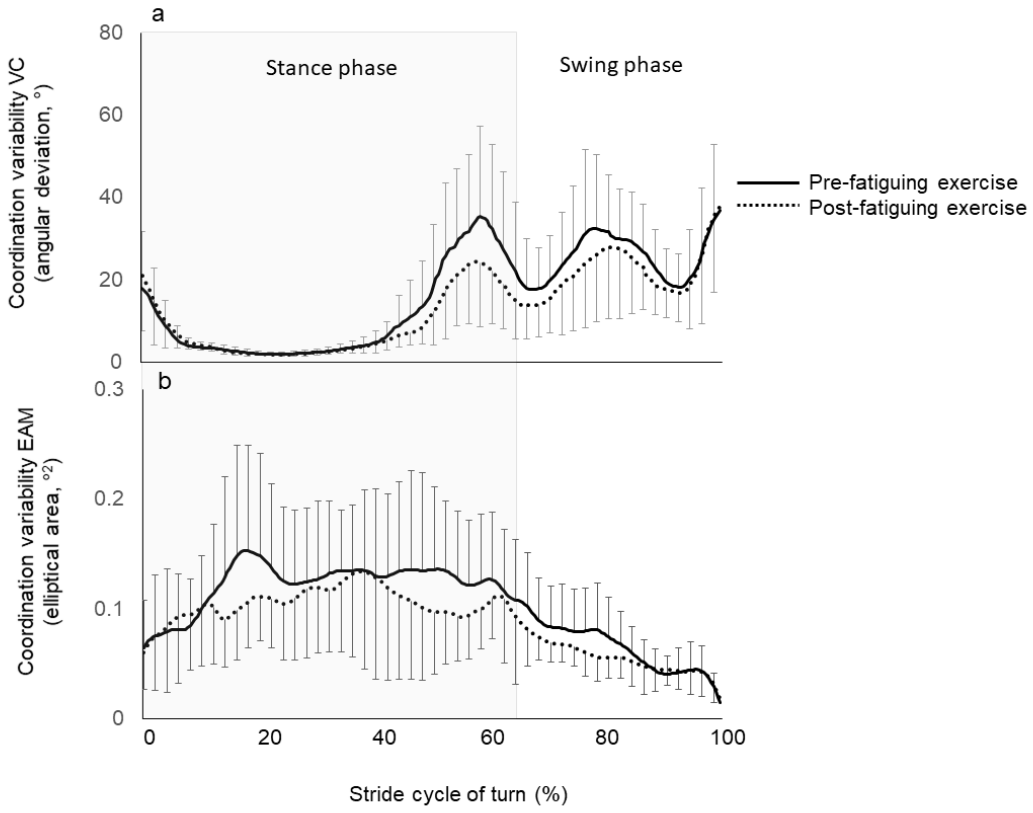

θ Trunk (Degrees)
θ Pelvis (Degrees)
A
B
C
ϕA
ϕB
ϕC
Δ θ Trunk
Δ θ Pelvis
# of Walking Turn Strides


a
Stance phase
Swing phase
Coordination variability VC (angular deviation, °)
80
60
40
20
0
Pre-fatiguing exercise
Post-fatiguing exercise
b
Coordination variability EAM (elliptical area, °²)
0.3
0.2
0.1
0
0
20
40
60
80
100
Stride cycle of turn (%)

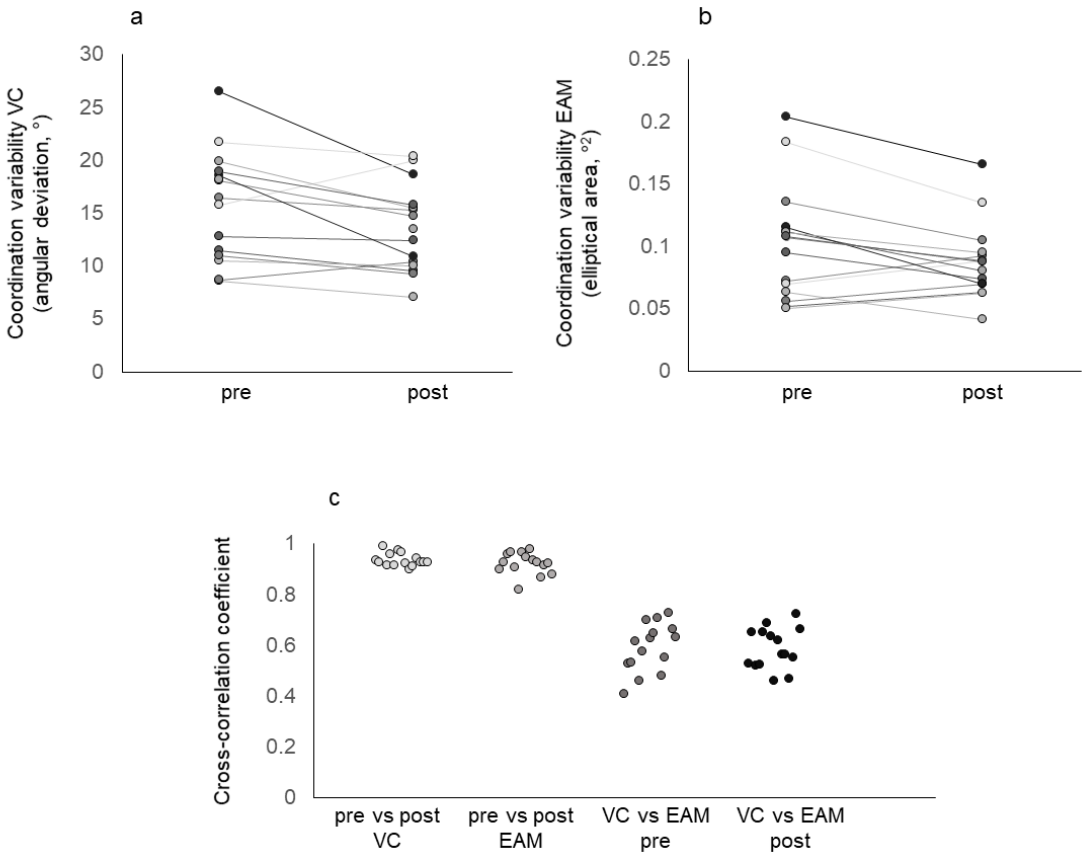

a
Coordination variability VC (angular deviation, °)
30
25
20
15
10
5
0
pre
post
b
Coordination variability EAM (elliptical area, °²)
0.25
0.2
0.15
0.1
0.05
0
pre
post
c
Cross-correlation coefficient
1
0.8
0.6
0.4
0.2
0
pre vs post VC
pre vs post EAM
VC vs EAM pre
VC vs EAM post

FIGURE LEGENDS

Figure 1. Stride cycle of a ipsilateral walking turn to the right. The stride cycle begins with initial contact of the right foot. Ninety-degree re-orientation is completed within the stance phase of the right foot. The area for the turn is outlined by cones to constrain the turning angle.

Figure 2. Simplified representation of the vector coding method (VC) and ellipse area method (EAM) for quantifying variability of trunk-pelvis coordination across multiple trials of a walking turn. a) Exemplar data showing an angle-angle plot of axial plane motion relative to the laboratory coordinate system for the trunk and pelvis during three walking turn trials. b) VC method. The pattern of coordination is quantified with the coupling angle of the vector connecting successive time points. Coupling angle for each of three exemplar time intervals during a single trial shown (ϕA, ϕB, ϕC). Coordination variability at each time interval is the angular deviation of each coupling angle across multiple trials. c) EAM method. The coordination variability across multiple trials for each of three exemplar time intervals (A, B, C) is the area of the ellipse encompassing the change in position during that time interval in each trial.

Figure 3. Ensemble-averaged time series of coordination variability across the stride cycle of the walking turn quantified by a) the vector coding method, and b) the ellipse area method. Stride cycle time normalized to 100%. Error bars indicate standard error of the mean.

Figure 4. Change in magnitude of variability from pre- to post-fatigue for each individual quantified with a) vector coding, and b) ellipse area method. Figure 4c. Individual cross correlation coefficients between the variability time series quantified pre- and post-fatigue with vector coding (VC), and ellipse area method (EAM).

Table 1. Average magnitude (± standard deviation) of coordination variability quantified with vector coding (VC) and ellipse area method (EAM) and effect sizes (ES) for pre-post comparisons.

	Pre	Post	p	ES
Stride cycle VC, °	15.78 ± 5.17	13.55 ± 4.08	0.016	0.78
Stance phase VC, °	10.56 ± 4.51	8.35 ± 2.93	0.022	0.70
Swing phase VC, °	24.96 ± 7.39	22.52 ± 7.29	0.033	0.60
Stride cycle EAM, °^{2}	0.10 ± 0.05	0.09 ± 0.03	0.034	0.79
Stance phase EAM, °^{2}	0.12 ± 0.06	0.10 ± 0.04	0.027	0.73
Swing phase EAM, °^{2}	0.07 ± 0.03	0.06 ± 0.01	0.222	0.33