Heliyon 10 (2024) e28345

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

In-vivo 3-dimensional spine and lower body gait symmetry analysis in healthy individuals

Paul G. Arauz [a,*], Maria-Gabriela Garcia [b], Patricio Chiriboga [b], Vinnicius Okushiro [b], Bonnie Vinueza [b], Kleber Fierro [b], José Zuñiga [b], Sebastian Taco-Vasquez [c], Imin Kao [d], Sue Ann Sisto [e]

[a] Department of Orthopaedics, Stony Brook University, Stony Brook, NY, United States
[b] Colegio de Ciencias e Ingenierías "El Politécnico", Universidad San Francisco de Quito USFQ, Quito, Pichincha, Ecuador
[c] Departamento de Ingeniería Química, Escuela Politécnica Nacional, Quito, Pichincha, Ecuador
[d] Department of Mechanical Engineering, Stony Brook University, Stony Brook, NY, United States
[e] Department of Rehabilitation Science, University at Buffalo, Buffalo, NY, United States

ARTICLE INFO

Keywords:
Gait symmetry
Statistical parametric mapping
Symmetry index
Overground
Walking
Sex
Speed
Spine kinematics
Lower body kinematics

ABSTRACT

Background: Numerous research studies have delved into the biomechanics of walking, focusing on the spine and lower extremities. However, understanding the symmetry of walking in individuals without health issues poses a challenge, as those with normal mobility may exhibit uneven movement patterns due to inherent functional differences between their left and right limbs. The goal of this study is to examine the three-dimensional kinematics of gait symmetry in the spine and lower body during both typical and brisk overground walking in healthy individuals. The analysis will utilize statistical methods and symmetry index approaches. Furthermore, the research aims to investigate whether factors such as gender and walking speed influence gait symmetry.

Methods: Sixty young adults in good health, comprising 30 males and 30 females, underwent motion capture recordings while engaging in both normal and fast overground walking. The analysis focused on interlimb comparisons and corresponding assessments of side-specific spine and pelvis motions.

Results: Statistical Parametric Mapping (SPM) predominantly revealed gait symmetries between corresponding left and right motions in the spine, pelvis, hip, knee, and ankle during both normal and fast overground walking. Notably, both genders exhibited asymmetric pelvis left-right obliquity, with women and men showing an average degree of asymmetry between sides of $0.9 \pm 0.1^{\circ}$ and $1.5 \pm 0.1^{\circ}$, respectively. Furthermore, the analysis suggested that neither sex nor walking speed appeared to exert influence on the 3D kinematic symmetry of the spine, pelvis, and lower body in healthy individuals during gait. While the maximum normalized symmetry index (SI_{norm}) values for the lower thorax, upper lumbar, lower lumbar, pelvis, hip, knee, and ankle displayed significant differences between sexes and walking speeds for specific motions, no interaction between sex and walking speed was observed.

Significance: The findings underscore the potential disparities in data interpretations between the two approaches. While SPM discerns temporal variations in movement, these results offer

* Corresponding author. Department of Orthopaedics, Renaissance School of Medicine, Stony Brook University, 101 Nicolls Road, Health Sciences Center, Stony Brook, NY 11794, United States.

E-mail address: paul.arauz@stonybrook.edu (P.G. Arauz).

https://doi.org/10.1016/j.heliyon.2024.e28345
Received 11 March 2023; Received in revised form 15 February 2024; Accepted 16 February 2024
Available online 22 March 2024
2405-8440/

valuable insights that may enhance our comprehension of gait symmetry in healthy individuals, surpassing the limitations of straightforward discrete parameters like the maximum SI_{norm}. The information gleaned from this study could serve as reference indicators for diagnosing and evaluating abnormal gait function.

1. Introduction

Clinical importance lies in the investigation of the three-dimensional (3D) joint kinematics of the lower limb and spine in the context of walking [1,2]. Understanding the intricacies of spine function and its connections with lower limb movements in individuals without health issues can contribute to improved preoperative planning. Understanding this information is crucial for re-establishing proper alignment and balance, while minimizing any negative impacts on walking in patients recovering from surgery [3]. The establishment of standards that differentiate between normal and pathological locomotion patterns has the potential to enhance clinical and functional outcomes, such as improved patient-reported outcomes, including knee and hip scores [4,5]. Numerous assessments have been conducted to compare impairment levels, pathologies, and movement disorders, such as those seen in patients with joint replacements, muscle strains, and low back injuries [2,4,5]. Consequently, a standardized reference derived from healthy individuals is imperative for evaluating and guiding interventions in patients with movement disorders.

Gait symmetry is identified by the synchronized motion of the left and right limbs while walking [6], is a valuable tool in medicine for the diagnosis and treatment of musculoskeletal disorders through symmetrical comparisons of affected and non-affected sides [2,4,5,7–10]. It acts as a vital measure of gait function in both individuals with impaired mobility and those without any mobility issues [4,5,11,12]. Research has highlighted that asymmetric gait is inefficient, leading to increased oxygen consumption and energy costs in locomotion [9,13]. Additionally, this could lead to an elevated dynamic burden on the opposite limb and joints, raising the likelihood of osteoarthritis and musculoskeletal injuries [14]. Compensatory asymmetrical movement patterns in the lumbar region have been observed in individuals with leg length discrepancy, contributing to the development of low back pain [15,16].

Hence, a comprehensive evaluation and description of typical spine and lower body symmetry during walking are crucial for the implementation and assessment of corrective interventions. Extensive literature exists on gait symmetry [12,17–23] along with research on the biomechanics of the spine and lower body during walking [4,5,11,24–29]. Numerous research studies have applied statistical techniques such as statistical parametric mapping (SPM) and symmetry indices to examine interlimb asymmetries in individuals with pathology. These investigations employ the average disparity between the left and right limbs as a measure to evaluate symmetry [4,5,10,23,30,31]. However, there is a notable absence of studies applying these methods to establish the baseline level of asymmetry in information for healthy individuals during overground walking.

Studies have indicated that gait kinematics are influenced by both sex and walking speed [1,32–34]. Typically, men walk faster and with greater pace than women [35,36]. Furthermore, previous studies have reported differences between the sexes regarding kinematic gait characteristics such as the range of motion in ankle and hip joints [36], and various parameters such as mechanical energy exchange within and between joints [35]. Previous work has shown that sex plays an important role in pathological conditions such osteoarthritis, anterior cruciate ligament (ACL) tears, and low back pain [37–41]. In addition, the design and improvement of patient-specific joint replacements, prosthetics, and rehabilitation interventions may be guided by sex difference [4,5,37,42–44]. However, as there exists conflicting information, it remains unclear if sex difference affects gait symmetry in healthy individuals [45]. In addition, while earlier research has documented how walking speed affects gait kinematics. [1,34], limited information exists on the impact of walking speed on gait symmetry. For instance, a report indicates that at lower speeds, feet are more prone to non-coupling and adopting diverse functional strategies, whereas at higher speeds, motion patterns tend to exhibit greater coupling and symmetry [46].

The literature has documented the impact of both sex and walking speed on gait kinematics [1,32–34]. Generally, men exhibit a faster and more vigorous walking pace compared to women [35,36]. Prior research has highlighted sex-related disparities in gait kinematics, encompassing variances in the range of motion within ankle and hip joints, along with distinctions in parameters like mechanical energy exchange both between and within joints [35,36].

Sex has been recognized as a significant factor in various pathological conditions, including low back pain, anterior cruciate ligament (ACL) tears, and osteoarthritis [37–41]. Moreover, the development and enhancement of patient-specific joint replacements, prosthetics, and rehabilitation interventions are influenced by sex differences [4,5,37,42–44]. However, conflicting information exists, leaving uncertainty about whether sex differences affect gait symmetry in healthy individuals [45]. Furthermore, although earlier studies have investigated how walking speed influences gait kinematics [1,34], there is insufficient information regarding the consequences of walking speed on gait symmetry. Notably, research suggests that at higher speeds feet tend to display increased coupling and symmetry in motion patterns, while at lower speeds, there is a higher likelihood of non-coupling in feet and the adoption of diverse functional strategies.

Therefore, this study aimed to utilize statistical and symmetry index approaches for three main objectives: 1) delineating the 3D kinematics of gait symmetry in the spine and lower body during both normal and fast overground walking in healthy individuals of both sexes, 2) evaluating the influence of sex on gait symmetry, and 3) assessing how walking speed influences gait symmetry. The findings of this study are pertinent for better understanding of gait asymmetry in healthy individuals, providing valuable reference indicators for the diagnosis and evaluation of abnormal gait function.

2. Materials & methods

2.1. Participants

This study comprised sixty unimpaired young adults, evenly distributed between genders (30 males and 30 females), with informed written consent as approved by the Ethics Committee of the Universidad San Francisco de Quito (IE03-EX145-2021-CEISH-USFQ), adhering to the principles of the Declaration of Helsinki. All participants maintained a healthy lifestyle, participating in physical exercise a minimum of two times per week, and did not have any known gait impairments, disabilities, history of surgery, autoimmune diseases, or cognitive issues. Among the sixty participants, fifty-two revealed a preference for their right leg, defining leg dominance as the favored leg for kicking a ball. The age and dominant side were mostly matched between the male and female groups. Table 1 provides a summary of the demographic information.

2.2. Instrumentation

Motion data were recorded using a 10-camera motion capture system (Vicon MX, Oxford, UK) operating at 100 Hz. A spatial volume of 5 × 5 × 4 cubic meters, providing an accuracy of 0.5 mm was covered by the cameras [11,47–49]. To capture spine and lower body motions, fifty-three 10 mm spherical reflective markers were strategically placed [11,27,30,50]. These markers, either single or in clusters of four, were affixed to participants' anatomical landmarks and segments using double-sided tape, as depicted in Fig. 1.

2.3. Procedures

All measurements took place at the Ergonomics Laboratory at Universidad San Francisco de Quito. Before the experiments, participant height (measured in meters) and mass (measured in kilograms) were obtained using a tape measure and a scale. The participants underwent both experimental conditions, normal and fast walking, within a single session. During normal walking, participants were instructed to maintain their usual relaxed pace, while in fast walking, they were directed to walk as swiftly as possible, as if they were running late, covering a 7-m distance. The order of each test condition was determined through random assignment, and every condition was iterated at least three times consecutively. Trials consisted of a minimum of three complete gait cycles, performed at a self-selected normal or fast pace. As a result, each test condition included a minimum of nine complete gait cycles from every participant.

2.4. Data processing

The analysis of gait kinematics required using the 3D global coordinates of each reflective marker with respect to a base reference frame (Vicon coordinate system) to compute 3D joint kinematics. The marker model introduced by Arauz et al. [30] was employed for the computation of spine and lower body kinematics, as illustrated in Figs. 1 and 2. This model mapped anatomical axes onto clusters representing the thigh, tibia, and foot, thereby calculating 3D joint rotations angles for the hip, knee, and ankle (Fig. 2) [11,30]. Joint rotations were computed using a Cardan *yxz* angle sequence [51], describing motions in the sagittal, coronal, and axial planes, respectively (Fig. 2). Positive rotations were assigned to flexion, right lateral flexion, right rotation, posterior tilt, right obliquity, adduction, internal rotation, dorsi-flexion, and eversion. The collected data were exported and analyzed using custom scripts in MATLAB (MathWorks, Inc., Natick, MA).

For each test condition, a comparison of gait kinematic measurements for the left and right limbs, as well as corresponding rotations of the spine and pelvis segments, was performed. Participants were instructed to stand upright with their feet aligned on floor marks, ensuring a standardized position with shoulder width and 30-degrees of abduction. The neutral position (zero degree) for all joints was defined using joint angles from the standing postures (Fig. 2). The angular data for joints was manually segmented into a single stride. Each time-normalized joint angle (ranging from 0 to 100%) representing the average gait cycle across all cycles for each condition was generated, with 1% sample steps [4,5,11], where 0% aligned with the heel strike of the relevant leg. Strides were defined from the

Table 1
Demographic data in female and male healthy participants. Data are the results of t-tests and chi-square tests.

	Female	Male	Mean Difference	95% CI	p-value
Number of participants	30	30			
Age (years)	21 ± 2 (18.0–26.0)	21 ± 2 (18.0–30.0)	−0.10	−1.5 to 1.31	0.886
Height (m)	1.60 ± 0.05 (1.47–1.75)	1.76 ± 0.06 (1.64–1.88)	−0.15	−0.18 to −0.12	**<0.001**
Mass (kg)	55.12 ± 8.81 (42.49–78.70)	71.52 ± 9.70 (51.5–96.0)	−16.40	−21.78 to −11.02	**<0.001**
BMI (kg/m^2)	21.45 ± 3.19 (16.19–31.13)	23.19 ± 2.72 (18.03–28.70)	−1.74	−3.35 to −0.14	**0.035**
Dominant side	25 right, 5 left	27 right, 3 left			0.445
Normal overground walking speed (m/s)	1.15 ± 0.13 (0.84–1.41)	1.24 ± 0.15 (0.91–1.64)	−0.09	−0.15 to −0.03	**0.006**
Fast overground walking speed (m/s)	1.71 ± 0.16 (1.43–2.15)	1.87 ± 0.20 (1.46–2.31)	−0.15	−0.25 to −0.06	**0.002**

Abbreviations: BMI, body mass index; CI, confidence interval.
Note: Boldfaced values indicate *p* values were significant at 0.05.

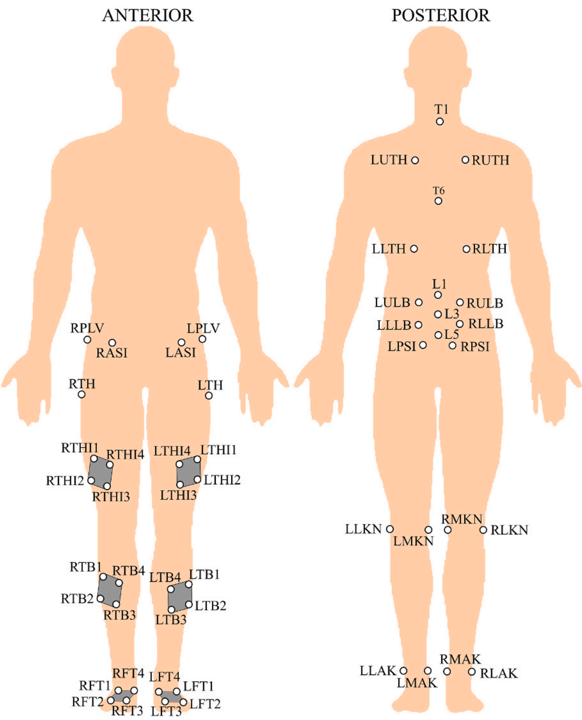


Fig. 1. Full body marker set. Prefixes denote the following: L: Left, R: Right, U: Upper, L: Lower, L: Lateral, and M: Medial. The following landmarks were used: Spinous process at T1 (T1), spinous process at T6 (T6), spinous process at L1 (L1), spinous process at L3 (L3), spinous process at L5 (L5), thorax (TH), lumbar (LB), anterior superior iliac spine (ASI), posterior superior iliac spine (PSI), femur (THI), epicondyle of femur (KN), tibia (TB), malleoli (AK), and foot (FT).

initial contact of one foot to the following initial strike [23,30].

To evaluate the kinematic gait symmetry of the lower limb and spine in each condition, rotation angles for the upper and lower thorax, lumbar segments, pelvis, hip, knee, and ankle joints were calculated.

Asymmetry, signifying a notable disparity in the joint angle patterns between the right and left sides, was assessed throughout the gait cycle by employing time-normalized waveforms for movements in the spine, pelvis, and lower body. To assess gait symmetry in the angular motions of the spine and pelvis, along with lower body joint angles, statistical parametric mapping and the normalized symmetry index, as introduced by Gouwanda et al. [21], were employed. The calculation of the normalized symmetry index (SI_{norm}) was performed using Eqs. (1) and (2), as outlined in previous studies [19–21,30,52].

$$SI_{norm} = \frac{X_{norm(R)} - X_{norm(L)}}{0.5 * \left(X_{norm(R)} + X_{norm(L)}\right)} * 100\% \tag{1}$$

with

$$X_{norm(n)} = \frac{X_n - X_{min}}{X_{max} - X_{min}} + 1 \tag{2}$$

2.5. Statistical analysis

To assess participant characteristics and differences between the normal and fast walking speed groups (Table 1), paired sample t-tests and chi-square tests were conducted using SPSS (IBM, SPSS V20, Chicago, IL). A three-way analysis of variance (ANOVA) employing Statistical Parametric Mapping (SPM) [11,30,53–57] was utilized to determine significant distinctions in the rotation angles between right and left sides of pelvis, hip, knee, and ankle joints, as well as the upper and lower thorax, lumbar segments. Additionally, this analysis explored interactions between side and speed, side and sex, and among side, speed, and sex.

All data satisfied the normality assumption based on the Kolmogorov-Smirnov and SPM 1d normality tests. Bonferroni corrections were applied for multiple tests in the SPM analyses across variables. A two-way ANOVA was employed to identify significant maximum SI_{norm}, differences for speed and sex and to explore their interactions. The statistical analysis was conducted in MATLAB (MathWorks, Inc., Natick, MA). The significance level was set at $\alpha = 0.05$, with the adjusted level following Bonferroni corrections set at $\alpha = 0.002$ due to 24 comparisons [58].

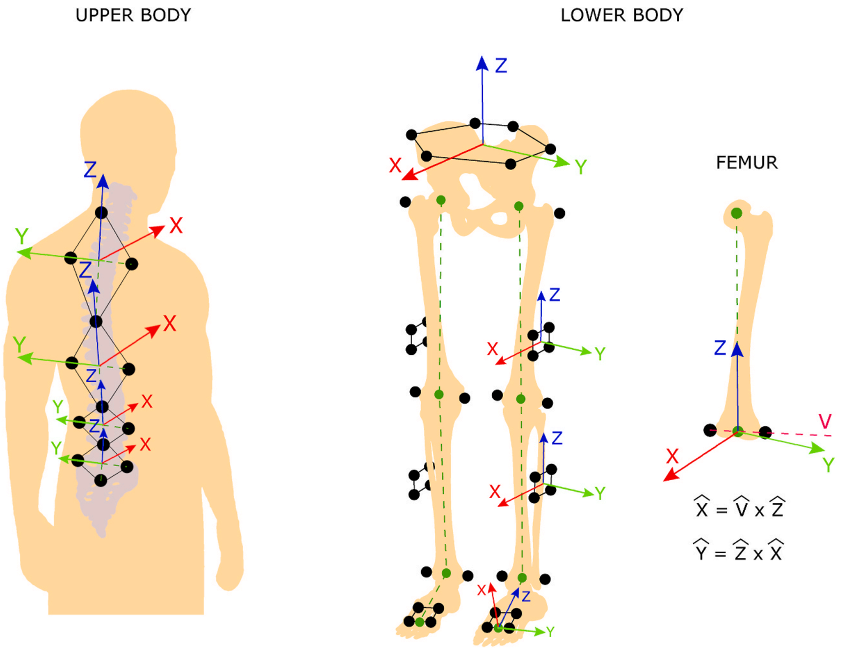


Fig. 2. Three-dimensional coordinate systems defined for upper thorax, lower thorax, upper lumbar, lower lumbar, pelvis, left and right thigh, left and right tibia, and left and right foot segments. Local *z* axes were determined between T1 and T6, T6 and L1, L1 and L3, and L3 and L5 for upper thorax, lower thorax, upper lumbar, and lower lumbar segments, respectively. Cross product of the *z* axis and the vector defined by the two midpoint markers determined the *x* axis of each spine segment. Joint angles defined for the upper thorax, lower thorax, upper lumbar, and lower lumbar. The left and right anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) markers defined the local pelvis axes, with the *y* axis defined between left and right ASIS, and the *x* axis pointing anteriorly. Anatomical hip, knee, ankle joint axes were projected on thigh, tibia, and foot clusters, respectively, with the local *z* axis along the long axis of the femur, tibia, and foot, and the local *y* axis pointing laterally.

3. Results

3.1. Walking speed

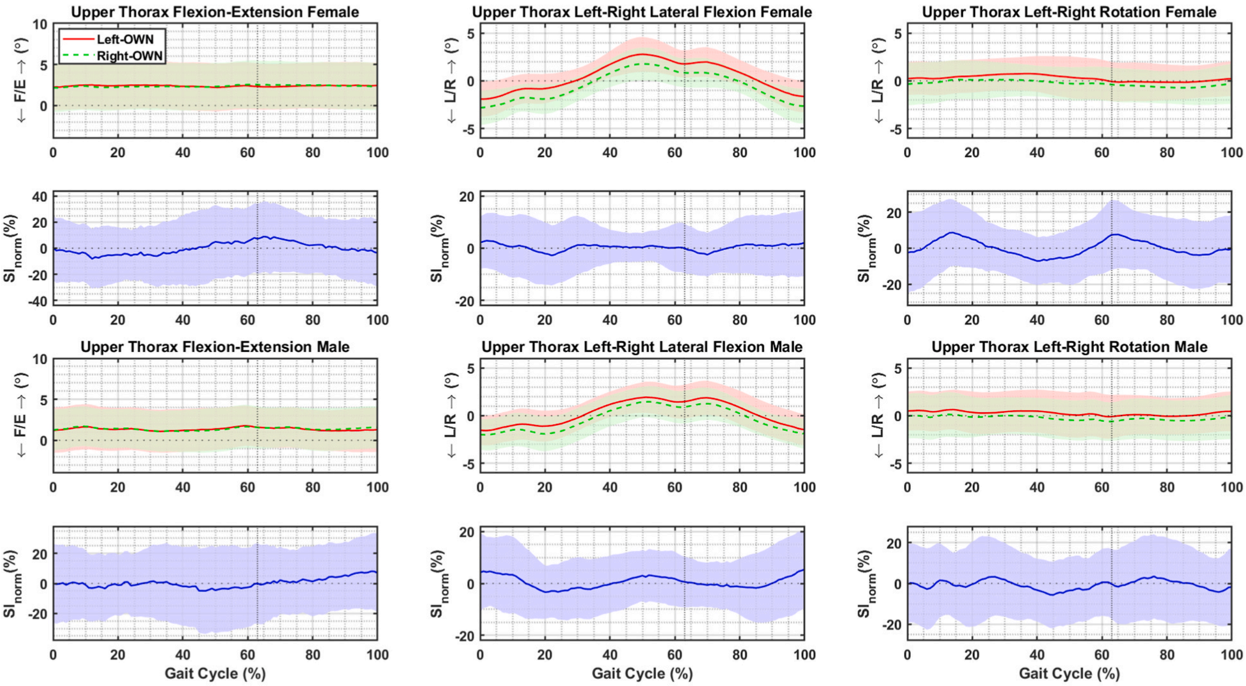
The average normal overground walking speed was 1.19 ± 0.15 (0.84–1.64) m/s. This differed significantly ($p < 0.001$) from the average fast overground walking speed 1.79 ± 0.2 (1.43–2.31) m/s. The average normal and fast walking speed of male participants was faster than the average normal and fast female walking speed at 1.24 ± 0.15 (0.91–1.64) m/s vs 1.15 ± 0.13 (0.84–1.41) m/s ($p = 0.006$) and 1.87 ± 0.20 (1.46–2.31) m/s vs 1.71 ± 0.16 (1.43–2.15) m/s ($p = 0.002$) (Table 1).

3.2. 3D overground walking symmetry kinematics

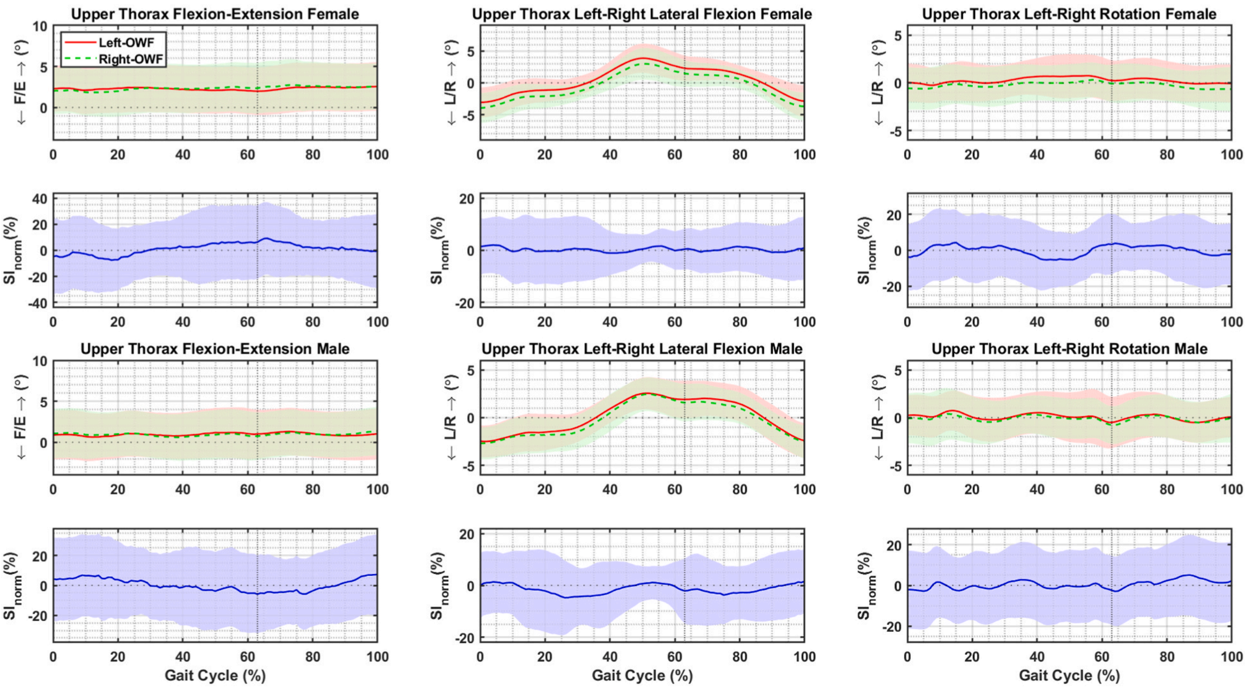
SPM analysis revealed that both female and male participants exhibited symmetry in upper thorax flexion-extension, left-right lateral flexion, and left-right rotation during both normal (Fig. 3a) and fast (Fig. 3b) overground walking, as the SPM curve remained below the critical threshold F*~15 for an adjusted $\alpha = 0.002$. There were no significant interactions observed between walking speed or sex and upper thorax symmetry. Further details of the three-way ANOVA SPM analysis can be found in Appendix A. The SI_{norm} values for upper thorax flexion-extension, left-right lateral flexion-extension, and left-right rotation were approximately within the ranges of ±36%, ±20%, and ±25%, respectively, for both female and male participants during both normal (Fig. 3a) and fast (Fig. 3b) overground walking.

Both sexes demonstrated symmetrical lower thorax flexion-extension, left-right lateral flexion, and left-right rotation during both normal (Fig. 4a) and fast (Fig. 4b) overground walking, as the SPM curve did not exceed the critical threshold F*~15 for an adjusted $\alpha = 0.002$. No significant associations were observed between walking speed or sex and lower thorax symmetry. SI_{norm} values for lower thorax flexion-extension, left-right lateral flexion-extension, and left-right rotation varied approximately between ±31%, ±20%, and ±15%, respectively, for both female and male participants during both normal (Fig. 4a) and fast (Fig. 4b) overground walking.

Both women and men displayed symmetrical upper lumbar flexion-extension, left-right lateral flexion, and left-right rotation in both normal (Fig. 5a) and fast (Fig. 5b) overground walking, as the SPM curve did not exceed the critical threshold F*~15 for an adjusted $\alpha = 0.002$. There were no significant associations observed between walking speed or sex and upper lumbar symmetry. SI_{norm} values for upper lumbar flexion-extension, left-right lateral flexion-extension, and left-right rotation varied approximately between ±30%, ±19%, and ±18%, respectively, for both female and male participants during both normal (Fig. 5a) and fast (Fig. 5b) overground walking.

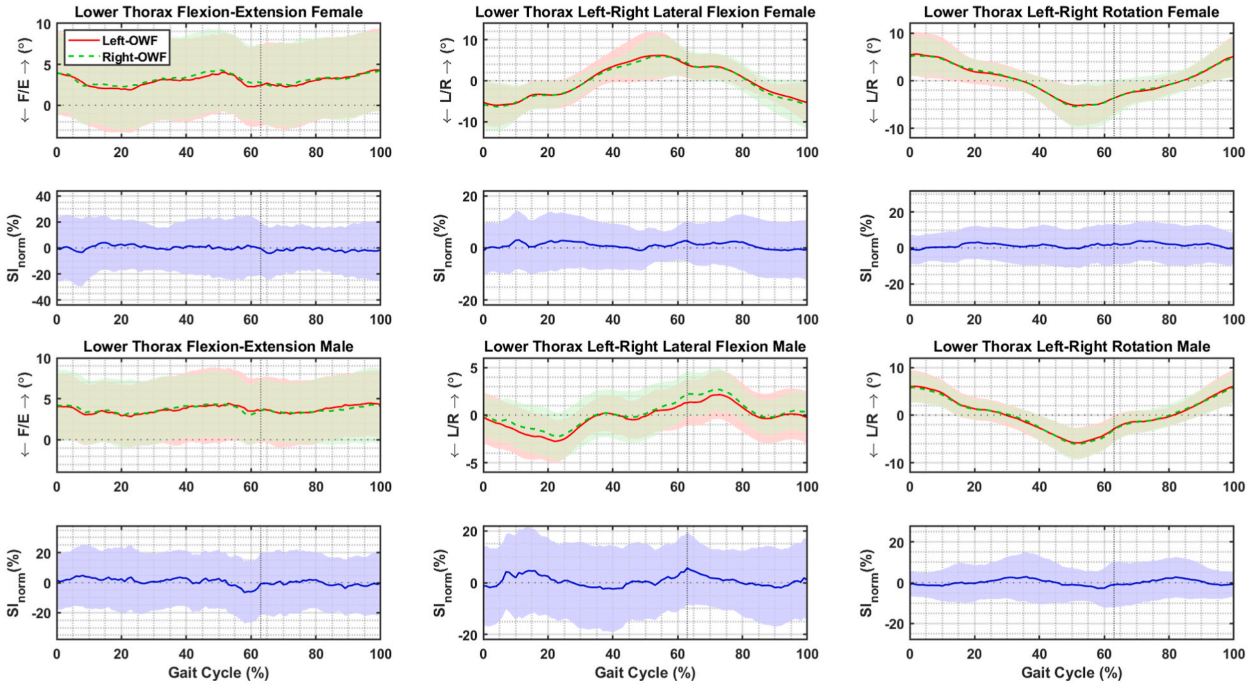


(a)

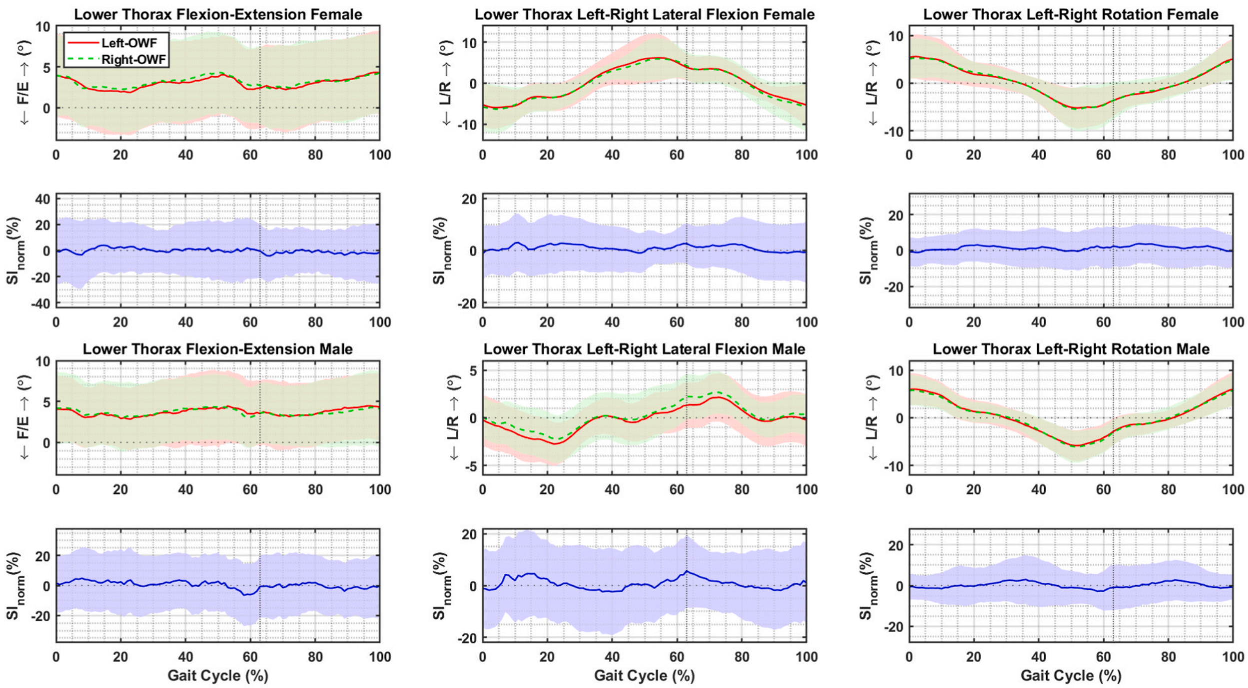


(b)

Fig. 3. Average and standard deviation of upper thorax flexion-extension (F/E), left-right (L/R) lateral flexion, and (L/R) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.



(a)



(b)

Fig. 4. Average and standard deviation of lower thorax flexion-extension (F/E), left-right (L/R) lateral flexion, and (L/R) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.

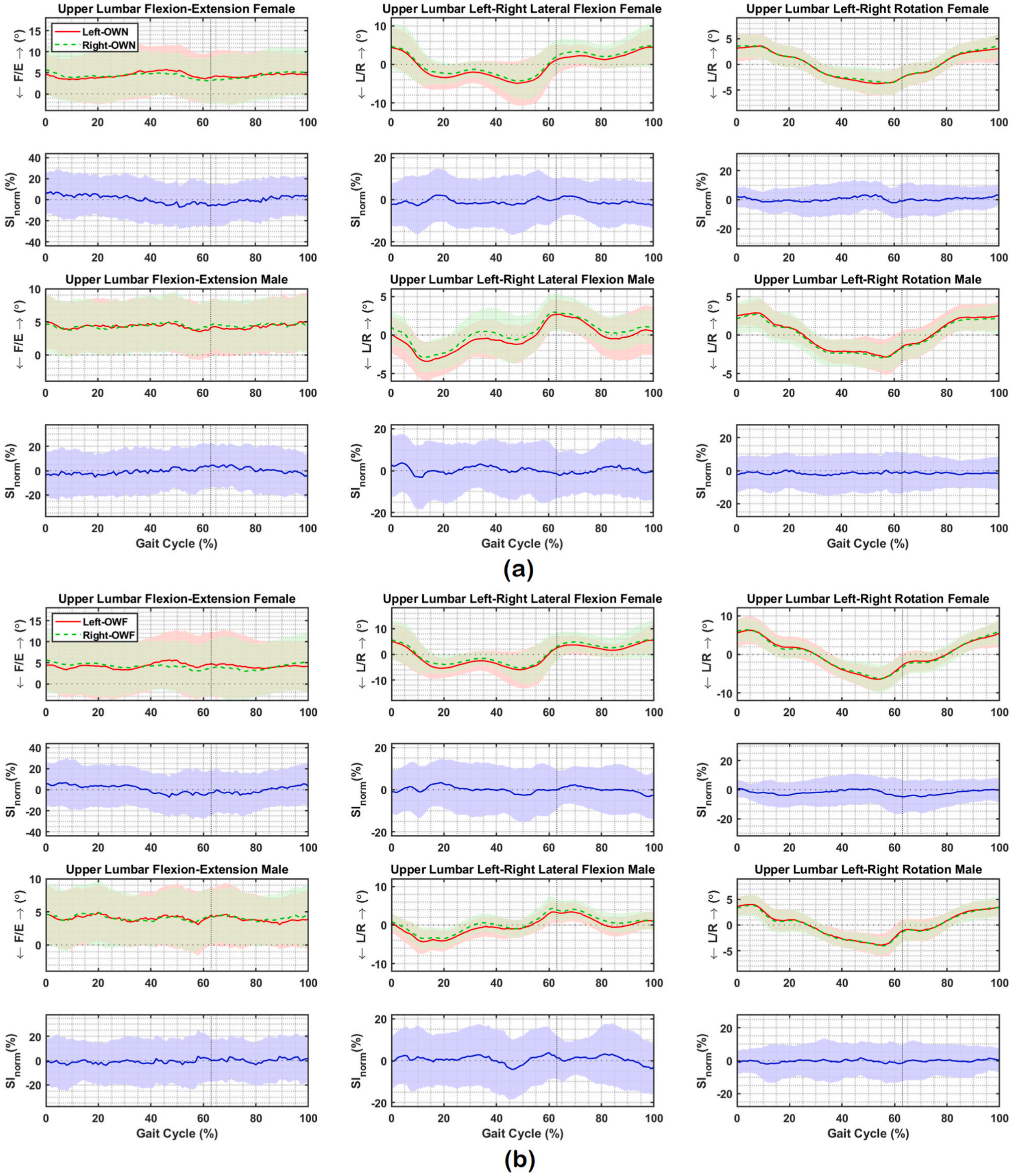


Fig. 5. Average and standard deviation of upper lumbar flexion-extension (F/E), left-right (L/R) lateral flexion, and (L/R) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.

Both female and male participants displayed balanced lower lumbar flexion-extension, left-right lateral flexion, and left-right rotation in both normal (Fig. 6a) and fast (Fig. 6b) overground walking, as the SPM curve remained below the critical threshold F*~15 for an adjusted α = 0.002. No significant associations were observed between walking speed or sex and lower lumbar symmetry.

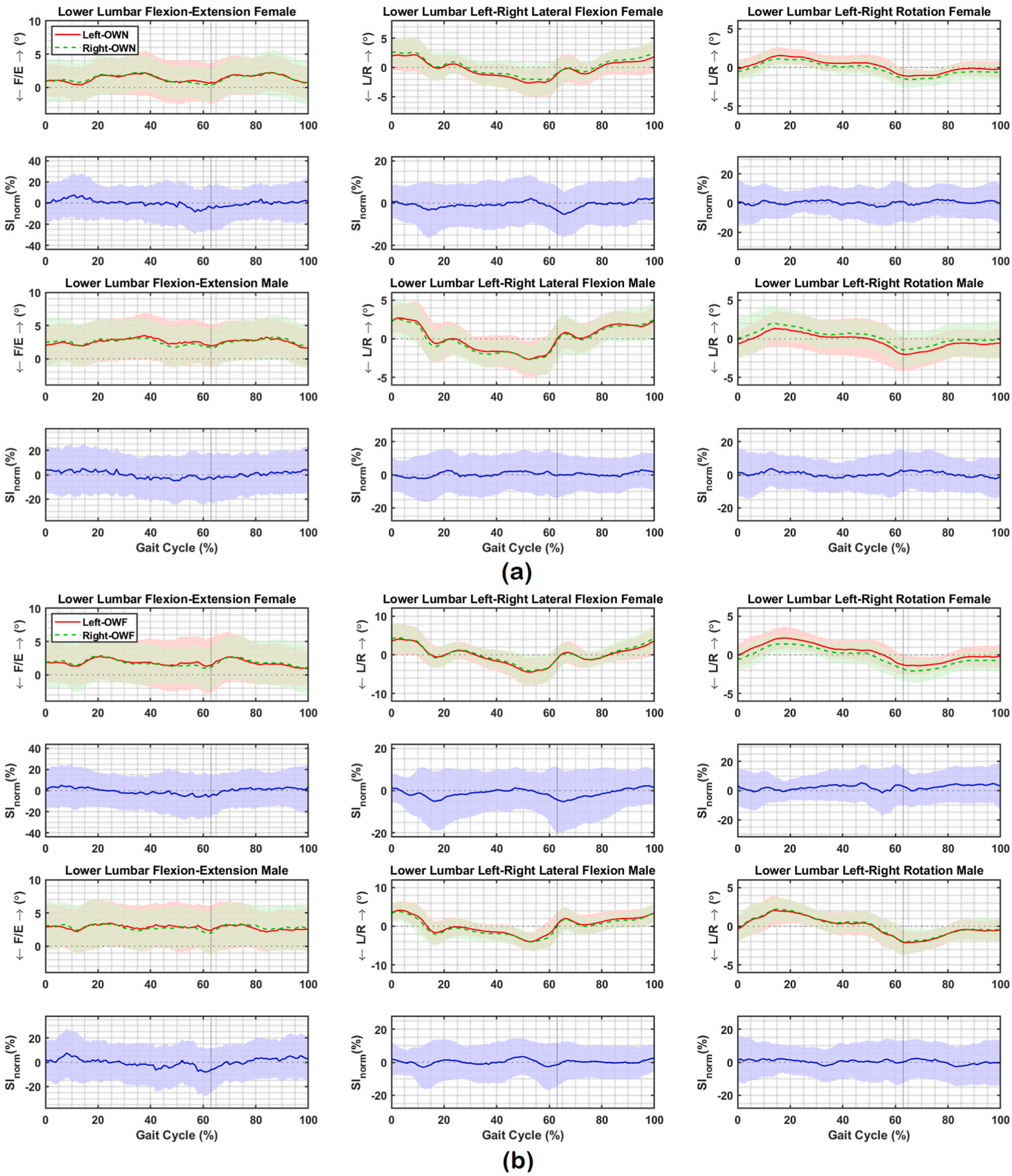


Fig. 6. Average and standard deviation of lower lumbar flexion-extension (F/E), left-right (L/R) lateral flexion, and (L/R) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.

SI_{norm} values for lower lumbar flexion-extension, left-right lateral flexion-extension, and left-right rotation varied approximately between ±27%, ±21%, and ±20%, respectively, for both female and male participants during both normal (Fig. 6a) and fast (Fig. 6b) overground walking.

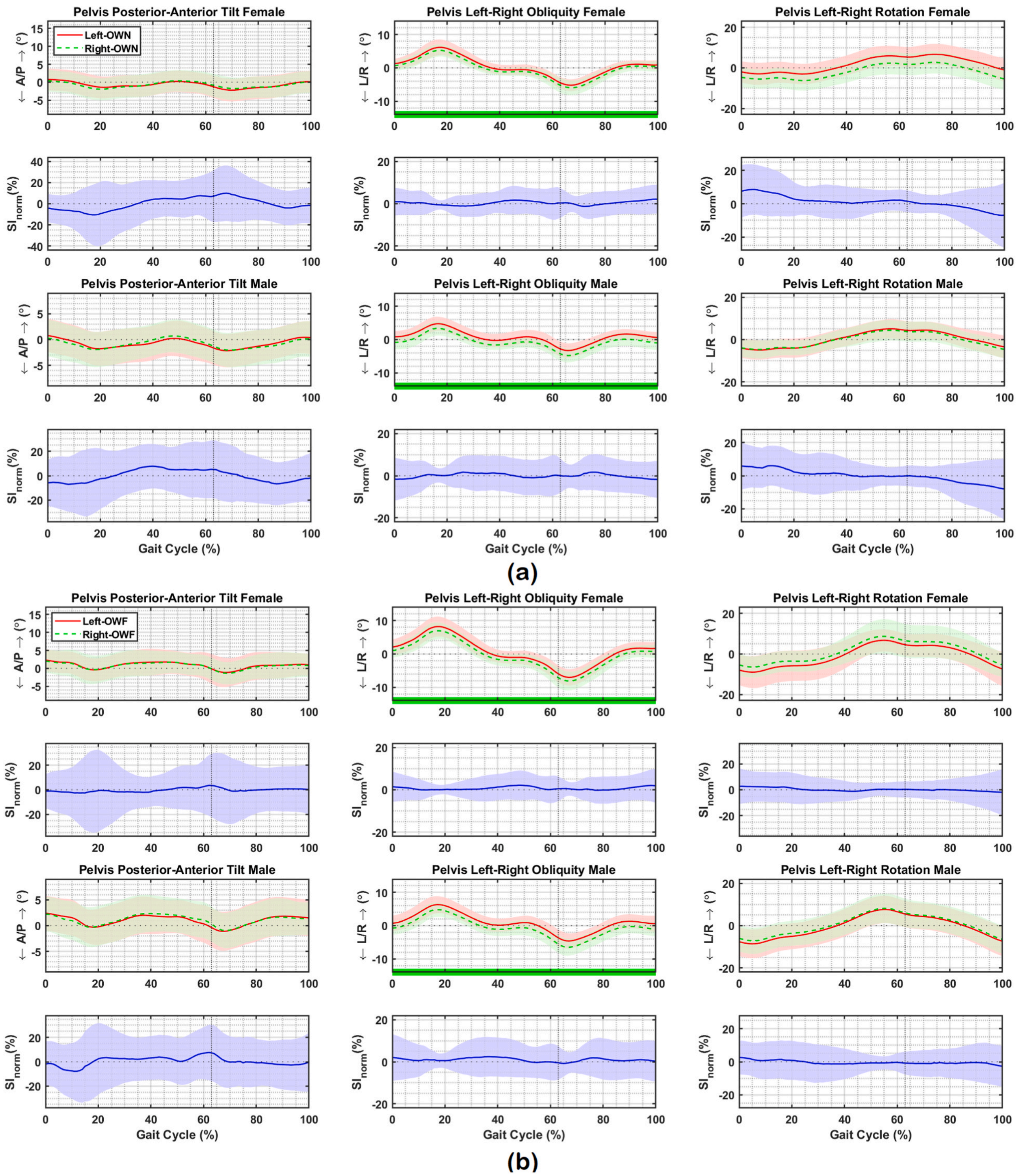
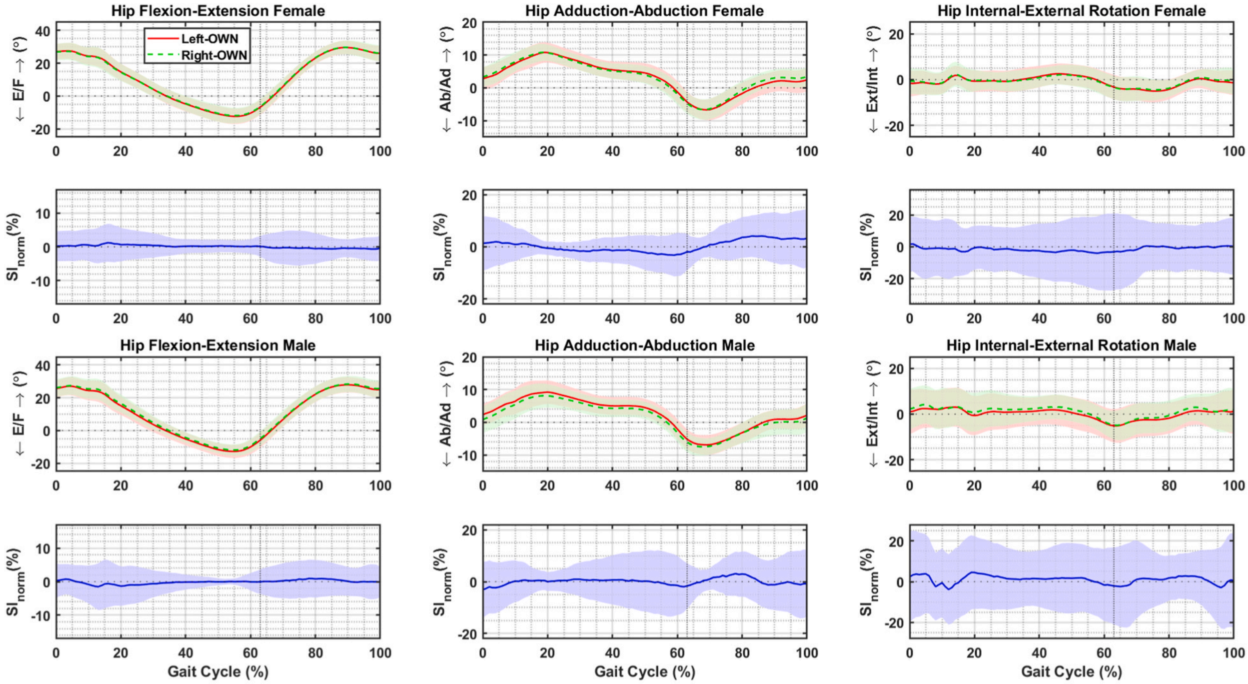
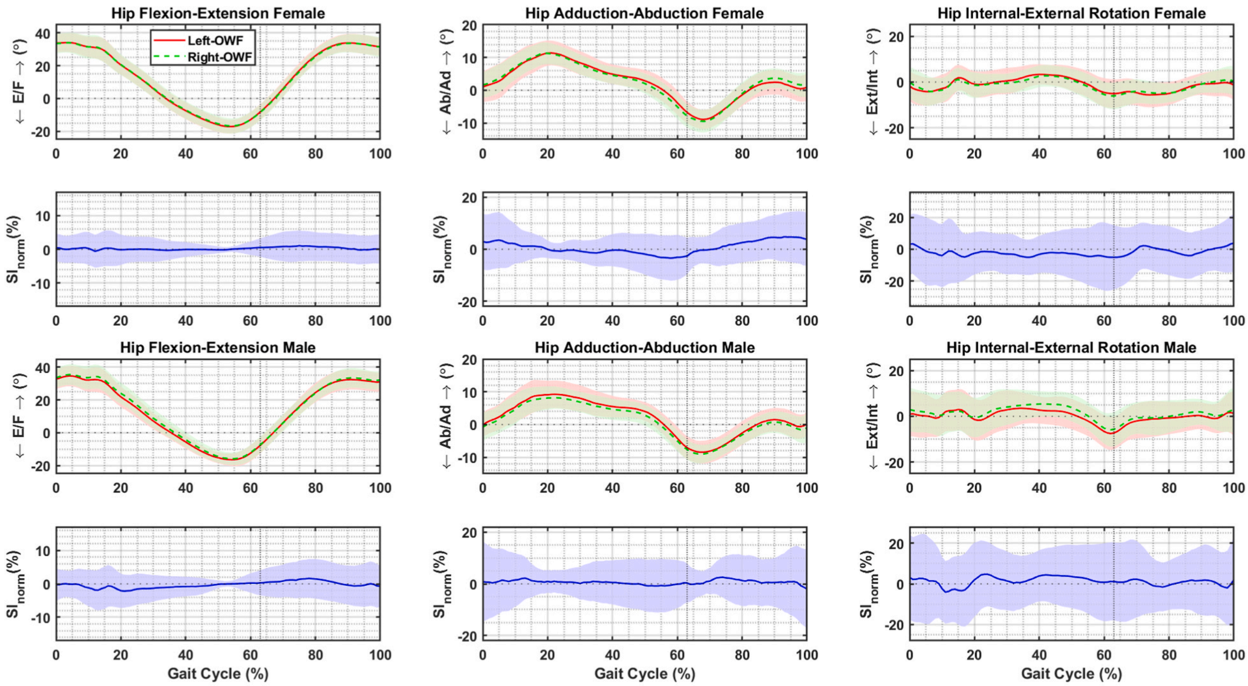


Fig. 7. Average and standard deviation of pelvis posterior-anterior (P/A) flexion, left-right (L/R) lateral obliquity, and (L/R) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. Green bars on the horizontal axis depict where, in % of gait cycle, left side angles were greater or lesser than right side angles. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



(a)



(b)

Fig. 8. Average and standard deviation of hip flexion-extension (F/E), adduction-abduction (Ad/Ab), and internal-external (Int/Ext) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.

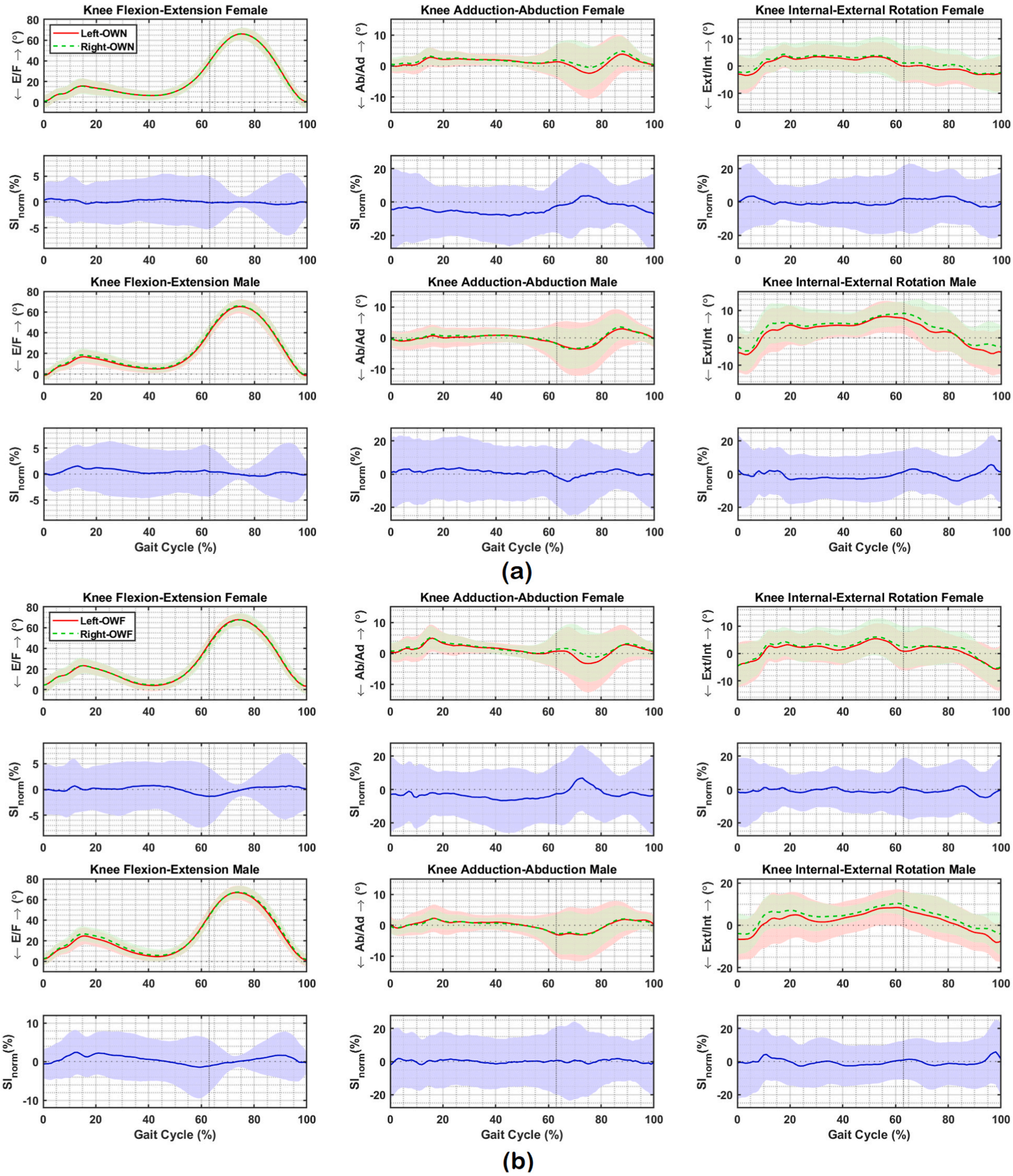


Fig. 9. Average and standard deviation of knee flexion-extension (F/E), adduction-abduction (Ad/Ab), and internal-external (Int/Ext) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.

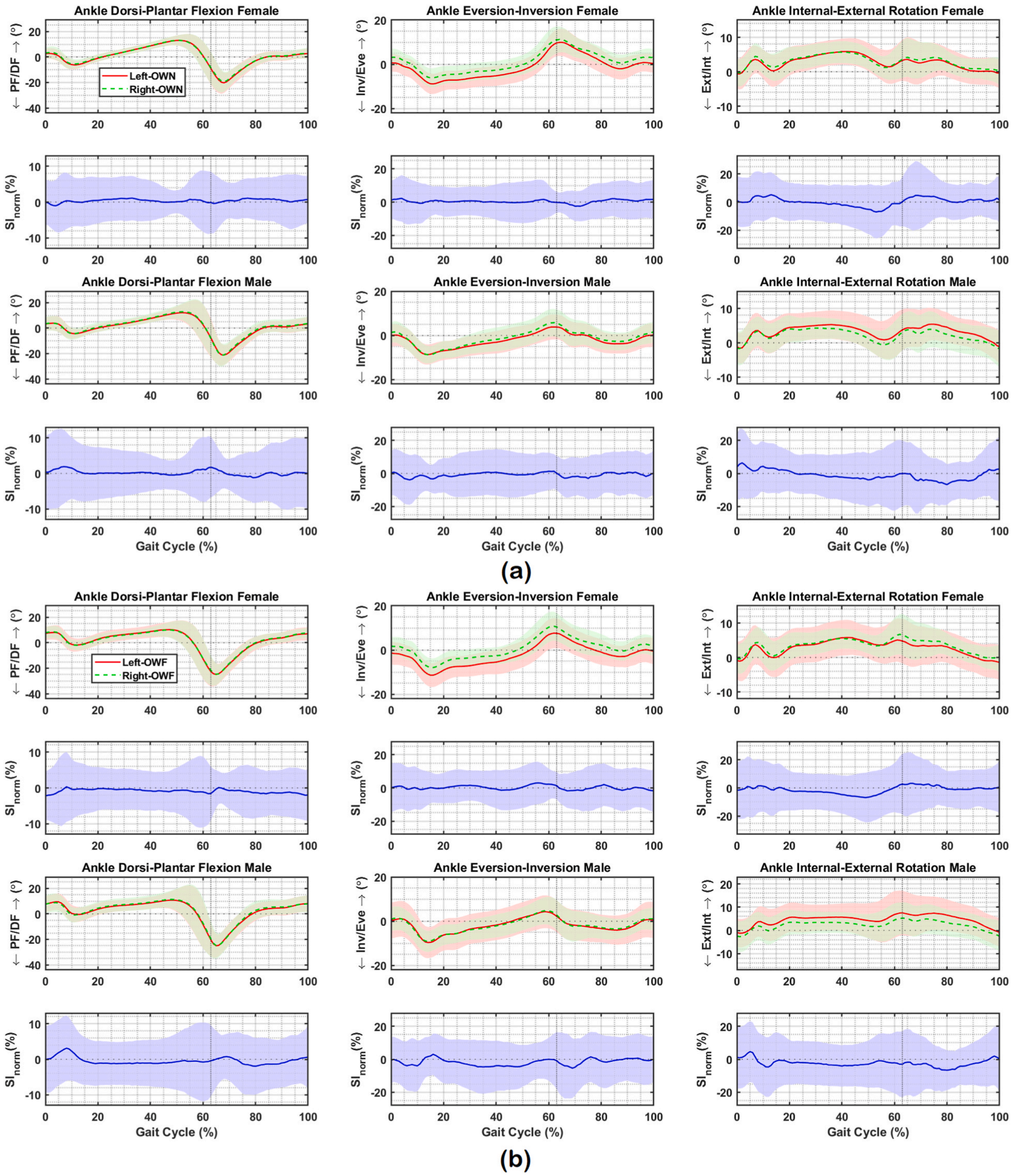


Fig. 10. Average and standard deviation of ankle dorsi-plantar flexion (DF/PF), eversion-inversion (Eve/Inv), and internal-external (Int/Ext) rotation, for left and right sides of males and females during one gait cycle of (a) normal overground walking (OWN) and (b) fast overground walking (OWF) in sixty healthy participants. The normalized symmetry index (SI_{norm}) calculated during one gait cycle of OWN and OWF. Solid and dashed lines correspond to average left and right sides, as well as average SI_{norm}, and shaded areas correspond to standard deviation. Black dotted vertical lines denote toe-off.

Table 2

Descriptive post-hoc statistics of the maximum SI_{norm} in % and its comparisons between female and male participants, as well as between normal and fast overground walking for N = 60 participants. A two-way ANOVA was used to determine if there is significant maximum SI_{norm} differences for sex and speed, and to compare its interactions between speed and sex. Bonferroni corrections for multiple comparisons (24 tests in total) were performed across all variables, and the p-values have been adjusted for $\alpha = 0.05/24 = 0.002$. Boldfaced values indicate p values were significant at 0.002.

Segment	Motion	Sex	Overground Normal Walking				Overground Fast Walking				*p-value*
			Mean	*SD*	*Max*	*Min*	*Mean*	*SD*	*Max*	*Min*	
Upper Thorax	*Flexion-Extension*	*Female*	47.36	10.92	66.67	17.89	43.55	12.40	66.42	13.98	0.031
		Male	46.56	12.33	66.67	14.51	43.93	11.56	63.13	13.06	0.097
		p-value	0.664				0.850				
	Left-Right Lateral Flexion	*Female*	16.54	10.94	41.59	0.92	16.89	9.07	47.96	1.31	0.739
		Male	17.11	9.73	47.91	1.74	21.31	11.13	60.12	4.94	0.007
		p-value	0.692				0.005				
	Left-Right Rotation	*Female*	30.18	15.01	65.08	1.07	29.36	15.15	66.33	0.63	0.658
		Male	31.60	13.17	66.67	2.35	30.04	13.70	61.67	4.90	0.365
		p-value	0.524				0.761				
Lower Thorax	*Flexion-Extension*	*Female*	43.23	10.27	66.67	11.86	47.57	10.80	66.58	18.06	**0.002**
		Male	44.93	10.36	66.67	20.75	46.42	9.06	64.97	23.49	0.230
		p-value	0.277				0.450				
	Left-Right Lateral Flexion	*Female*	18.45	9.92	50.83	3.30	17.20	10.06	45.28	3.285	0.266
		Male	28.71	12.69	59.80	4.13	26.57	12.79	60.53	2.021	0.150
		p-value	**<0.001**				**<0.001**				
	Left-Right Rotation	*Female*	18.45	9.49	45.74	1.57	19.06	10.03	46.07	2.90	0.577
		Male	15.91	7.95	36.76	2.68	16.58	9.19	45.95	1.43	0.557
		p-value	0.054				0.096				
Upper Lumbar	*Flexion-Extension*	*Female*	46.00	10.66	66.67	23.83	43.27	11.18	65.63	17.93	0.073
		Male	43.10	9.62	64.33	20.13	44.61	8.36	66.67	27.62	0.266
		p-value	0.083				0.380				
	Left-Right Lateral Flexion	*Female*	17.99	10.95	56.09	1.46	17.28	10.13	44.81	3.42	0.520
		Male	24.54	12.99	60.56	2.33	25.12	12.69	57.07	2.75	0.667
		p-value	**<0.001**				**<0.001**				
	Left-Right Rotation	*Female*	14.63	8.66	42.51	1.54	17.97	8.34	41.68	2.99	**0.002**
		Male	18.41	8.32	46.55	3.00	17.92	9.53	44.79	1.31	0.647
		p-value				0.004				0.970	
Lower Lumbar	*Flexion-Extension*	*Female*	42.54	9.71	63.01	22.82	42.47	10.54	64.73	19.98	0.963
		Male	44.42	10.06	66.06	22.64	45.40	9.98	66.67	20.05	0.519
		p-value	0.262				0.074				
	Left-Right Lateral Flexion	*Female*	18.70	9.93	64.77	2.12	16.79	10.40	51.34	2.80	0.065
		Male	23.01	10.93	53.86	4.10	22.94	11.92	61.08	5.24	0.965
		p-value	0.005				**<0.001**				
	Left-Right Rotation	*Female*	25.05	10.84	50.99	4.33	21.75	8.54	46.45	4.94	0.013
		Male	22.08	9.63	51.65	2.19	22.95	9.70	59.78	4.48	0.480
		p-value	0.063				0.400				
Pelvis	*Posterior-Anterior Tilt*	*Female*	38.76	13.46	62.20	3.15	35.62	12.94	65.46	9.73	0.069
		Male	38.38	12.66	64.39	10.95	36.06	12.17	62.67	12.46	0.098
		p-value	0.831				0.807				
	Left-Right Obliquity	*Female*	9.11	5.62	27.13	0.18	9.24	5.76	28.95	1.02	0.859
		Male	13.60	7.15	41.65	2.40	12.03	6.01	30.83	1.43	0.062
		p-value	**<0.001**				0.002				
	Left-Right Rotation	*Female*	16.39	9.53	39.29	0.16	19.94	11.86	55.02	2.41	0.015
		Male	14.21	9.63	49.06	1.27	17.38	11.71	54.95	0.63	0.017
		p-value	0.159				0.149				
Hip	*Flexion-Extension*	*Female*	7.30	3.00	17.14	1.43	6.68	3.92	21.60	1.78	0.266
		Male	8.19	3.53	20.15	0.83	8.02	4.05	19.42	0.79	0.730
		p-value	0.070				0.034				
	Adduction-Abduction	*Female*	16.17	8.90	49.32	2.35	13.41	6.94	40.91	1.88	**0.001**
		Male	18.47	9.04	43.28	2.21	14.72	7.26	32.21	4.65	**<0.001**
		p-value	0.106				0.254				
	Internal-External Rotation	*Female*	29.71	12.60	63.34	9.76	28.99	12.45	54.82	5.42	0.586
		Male	34.03	14.75	64.12	5.03	31.17	15.70	65.16	4.03	0.021
		p-value	0.023				0.261				
Knee	*Flexion-Extension*	*Female*	8.48	4.11	18.13	0.58	6.93	3.21	15.51	0.92	**0.001**
		Male	9.79	4.52	21.16	0.98	7.47	4.29	21.95	0.72	**<0.001**
		p-value	0.035				0.360				
	Adduction-Abduction	*Female*	29.25	13.62	59.45	4.17	28.46	12.58	66.26	4.05	0.560
		Male	32.23	14.07	66.67	9.78	30.43	15.33	66.67	6.63	0.086
		p-value	0.177				0.376				

(*continued on next page*)

Table 2 (*continued*)

Segment	Motion	Sex	Overground Normal Walking				Overground Fast Walking				*p-value*
			Mean	*SD*	*Max*	*Min*	*Mean*	*SD*	*Max*	*Min*	
	Internal-External Rotation	*Female*	27.48	11.61	62.90	8.46	30.69	12.39	60.02	8.15	0.046
		Male	29.67	13.29	65.67	7.03	27.46	13.55	64.83	2.74	0.092
		p-value	0.237				0.141				
Ankle	*Dorsi-Plantar Flexion*	*Female*	11.97	6.67	34.62	0.48	11.10	6.00	33.76	0.97	0.334
		Male	15.28	7.58	41.91	3.29	13.05	7.88	38.35	1.41	0.062
		p-value	**0.001**				0.090				
	Eversion-Inversion	*Female*	20.35	10.52	64.02	3.35	19.78	9.49	55.30	3.86	0.661
		Male	24.18	10.22	51.83	6.01	21.28	7.90	46.79	7.03	0.011
		p-value	0.016				0.181				
	Internal-External Rotation	*Female*	32.86	12.89	65.21	4.18	32.48	13.89	66.67	5.98	0.789
		Male	30.86	10.47	60.21	9.56	31.45	14.64	60.39	3.20	0.689
		p-value	0.271				0.641				

Both sexes displayed balanced pelvis posterior-anterior tilt and left-right rotation during both normal (Fig. 7a) and fast (Fig. 7b) overground walking, as the SPM curve remained below the critical threshold $F^{*}\sim15$ for an adjusted $\alpha = 0.002$. However, both genders presented asymmetry in pelvis left-right obliquity ($p < 0.001$) throughout the entire gait cycle. The average degree of asymmetry in pelvis left-right obliquity was $0.9 \pm 0.1^{\circ}$ for women and $1.5 \pm 0.1^{\circ}$ for men. No significant associations were observed between walking speed or sex and pelvis symmetry. SI_{norm} values for pelvis posterior-anterior tilt, left-right obliquity, and left-right rotation fluctuated approximately between ±40%, ±12%, and ±25%, respectively, for both female and male participants during both normal (Fig. 7a) and fast (Fig. 7b) overground walking.

Both men and women displayed consistent hip flexion-extension, abduction-adduction, and internal-external rotation during both normal (Fig. 8a) and fast (Fig. 8b) overground walking, as the SPM curve remained below the critical threshold $F^{*}\sim15$ for an adjusted $\alpha = 0.002$. No significant associations were observed between walking speed or sex and hip symmetry. SI_{norm} values for hip flexion-extension, abduction-adduction, and internal-external rotation fluctuated approximately between ±8%, ±12%, and ±22%, respectively, for both female and male participants during both normal (Fig. 8a) and fast (Fig. 8b) overground walking.

Both females and males displayed consistent knee flexion-extension, abduction-adduction, and internal-external rotation during both normal (Fig. 9a) and fast (Fig. 9b) overground walking, as the SPM curve remained below the critical threshold $F^{*}\sim15$ for an adjusted $\alpha = 0.002$. No significant associations were observed between walking speed or sex and knee symmetry. SI_{norm} values for knee flexion-extension, abduction-adduction, and internal-external rotation fluctuated approximately between ±10%, ±27%, and ±26%, respectively, for both female and male participants during both normal (Fig. 9a) and fast (Fig. 9b) overground walking.

Both males and females exhibited harmonious ankle dorsi-plantar flexion, eversion-inversion, and internal-external rotation during both normal (Fig. 10a) and fast (Fig. 10b) overground walking, as the SPM curve did not exceed the critical threshold $F^{*}\sim15$ for an adjusted $\alpha = 0.002$. No significant associations were observed between walking speed or gender and ankle symmetry. SI_{norm} values for ankle dorsi-plantar flexion, eversion-inversion, and internal-external rotation varied approximately between ±12%, ±20%, and ±25%, respectively, for both female and male participants during both normal (Fig. 10a) and fast (Fig. 10b) overground walking.

3.3. Maximum normalized symmetry index

Table 2 provides descriptive statistics for the maximum SI_{norm} and its comparisons between normal and fast overground walking, as well as between male and female participants. Post hoc comparisons, utilizing an adjusted $\alpha = 0.002$, revealed interactions between sex and speed for the SI_{norm} across all segments and joints. Specifically, men demonstrated a significantly higher ($p < 0.001$) maximum SI_{norm} for lower thorax and upper lumbar left-right lateral flexion during both normal and fast overground walking (Table 2) compared to women. Men also exhibited a significantly higher ($p < 0.001$) maximum SI_{norm} for lower lumbar left-right lateral flexion during fast overground walking compared to women (Table 2). Additionally, the maximum SI_{norm} for pelvis left-right lateral obliquity was significantly higher ($p < 0.001$) for men than women during normal overground walking (Table 2). Notably, hip adduction-abduction showed a significantly higher ($p < 0.001$) maximum SI_{norm} during normal compared to fast overground walking for both women and men (Table 2). Furthermore, knee flexion-extension demonstrated a significantly higher ($p < 0.001$) maximum SI_{norm} during normal compared to fast overground walking for both female and male participants (Table 2). Lastly, ankle dorsi-plantar flexion exhibited a significantly higher ($p < 0.001$) maximum SI_{norm} for men than women during normal overground walking (Table 2).

4. Discussion

This study aimed to explore the three-dimensional kinematics of gait symmetry in the spine and lower body during both normal and fast overground walking in a group of 60 young and healthy individuals. The study utilized statistical methods and symmetry index analyses. Additionally, the study sought to evaluate whether sex and walking speed exerted an influence on gait symmetry. Through Statistical Parametric Mapping (SPM) analyses, minimal gait asymmetries were observed in terms of 3D kinematics between the left and right-sided spine, pelvis, and lower body motions in both male and female participants. Specifically, both sexes exhibited asymmetric pelvis left-right obliquity, with women and men displaying average degrees of asymmetry between sides of $0.9 \pm 0.1^{\circ}$ and

1.5 ± 0.1°, respectively. Furthermore, the study revealed that neither sex nor walking speed significantly impacted the 3D spine, pelvis, and lower body kinematic symmetry during gait in healthy individuals. Although maximum SI_{norm} values differed between sexes or walking speeds for specific motions, no interactions were detected between sexes and walking speeds. These findings highlight that the two analytical approaches can yield different interpretations of the data. However, SPM, by identifying temporal differences in movement, provides insights into gait symmetry in healthy individuals that may not be captured by simple discrete parameters like maximum SI_{norm}. This information may serve as valuable reference indicators in restorative and rehabilitation interventions.

The existing literature has extensively established that gait kinematics exhibit variations among men, women, and different ethnic groups [32,33,36,37,59–61]. These disparities are often attributed to multifactorial influences, with sex-specific and morphological characteristics of the human body, such as bone and muscle shape and dimensions, considered significant contributing factors [33]. In the present study, female participants demonstrated increased pelvis left-right obliquity (coronal or frontal plane motion) and hip internal rotation (transverse or axial plane motion) during specific periods of the gait cycle compared to their male counterparts (Figs. A5b and A6c). These findings align with prior research indicating differences in frontal plane pelvis and hip joint angles between unimpaired males and females [32,36,37,59–61]. Such motion differences, particularly increased frontal plane hip motion along with hip abductor muscle weakness, have been associated with conditions like patellofemoral syndrome or iliotibial band syndrome in unimpaired females compared to males [37,62,63].

Moreover, our results partially align with previous studies showing that unimpaired males tend to exhibit higher knee flexion during the stance phase compared to females (Fig. A7a) [37,59,64]. Therefore, performing a thorough evaluation and characterization of normative gait differences between sexes is vital for the effective implementation and assessment of rehabilitative interventions.

Interestingly, despite several observed differences between men and women, our SPM findings suggested no interactions between sex and gait symmetry. These results diverged from the maximum SI_{norm} outcomes. Such disparities can be explained by SPM's ability to identify movement differences over time. In our study, SPM analysis identified pelvis left-right obliquity asymmetries in both male and female participants, which, rather than indicating abnormality, may be linked to the unique contributions of each extremity to propulsion and task control [11,65].

While the presence of 3D asymmetries in healthy individuals during normal and fast overground walking is expected, the degree of asymmetry remains a crucial indicator of gait function in both unimpaired and impaired individuals. The current study contributes by providing SI_{norm} values over time for healthy individuals, serving as valuable indicators for analyzing gait symmetry in clinical populations. These indicators can be particularly useful in the analysis of gait symmetry in individuals with total hip [5,10] or knee [4] replacements. Our SI_{norm} results for spine and lower body motions align with those reported in previous studies for treadmill walking [30]and overground walking [23]. Additionally, this study extends our understanding of the SI_{norm} indicator by detailing 3D angular motions of the spine, pelvis, and lower body during overground walking over time.

Despite well-established associations between walking speed and gait kinematics [1,45], our SPM findings suggest that walking speed may not significantly impact the in vivo 3D spine, pelvis, and lower body kinematic symmetry in healthy individuals during gait. It has been noted that at lower speeds, feet are more prone to non-coupling, and different functional strategies are employed, while at higher speeds, motion patterns exhibit increased coupling and symmetry [46]. Therefore, one plausible explanation for the observed symmetric motions in this study could be attributed to the motor control of gait being less challenged during both normal and fast walking [66,67]. This less challenging environment may facilitate better movement coordination among participants during the investigated normal and fast overground walking speeds. Consequently, the findings of this study may serve as a valuable indicator of gait motor control at various walking speeds.

The results of the current study need to be interpreted considering several limitations. Firstly, the participants in this study were predominantly around 21 years old and reported a healthy lifestyle (exercised at least twice a week), potentially limiting the generalizability of the findings to different age groups or less active populations. Secondly, the use of a limited number of gait cycles in both normal and fast overground walking conditions may not fully capture gait asymmetry kinematics during longer walking periods. Thirdly, the skin-marker-based tracking technique utilized is susceptible to soft tissue artifacts [68]. However, the use of clusters with at least four markers in most segments, except for the spine segments, aimed to minimize the impact of soft tissue artifacts. Additionally, leg dominance was not explicitly considered in the comparison of left and right limbs and their associated motions, although the majority of participants reported right-leg dominance. Leg length discrepancy was not addressed, although all participants were healthy and did not exhibit apparent leg length differences. Finally, the study did not analyze ground reaction force or electromyography (EMG) data, limiting the assessment of body kinetics and muscle activation patterns. Future studies should incorporate joint kinetics, ground reaction forces, and EMG data to provide a more comprehensive understanding of sex-specific asymmetries in gait biomechanics.

5. Conclusions

In conclusion, the outcomes of this study highlight that the two analytical approaches can lead to distinct data interpretations. Nevertheless, the identification of movement differences throughout the gait cycle by SPM offers valuable insights, providing a deeper understanding of gait symmetry in healthy individuals beyond what simple discrete parameters like maximum SI_{norm} may convey. This study introduces reference indicators that can be employed in restorative and rehabilitation interventions, enhancing the potential for effective treatment strategies.

Declarations

Prior to data collection, participants signed an informed consent form approved by the Ethics Committee of the Universidad San Francisco de Quito (IE03-EX145-2021-CEISH-USFQ). The present study complied with the tenets of the Declaration of Helsinki.

Data availability

This study data is publicly available at the following DOI: https://zenodo.org/records/10659624.

CRediT authorship contribution statement

Paul G. Arauz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Maria-Gabriela Garcia:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Patricio Chiriboga:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Vinnicius Okushiro:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Bonnie Vinueza:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Kleber Fierro:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **José Zuñiga:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Sebastian Taco-Vasquez:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Imin Kao:** Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Sue Ann Sisto:** Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The experimental study was performed at the Ergonomics Laboratory at Universidad San Francisco de Quito USFQ.

Appendix A

SPM analysis demonstrated that female and male participants displayed symmetrical upper thorax flexion extension, left-right lateral flexion, and left-right rotation during normal and fast overground walking as the SPM curve did not exceed the critical threshold $F^* \sim 15$ for adjusted $\alpha = 0.002$ (Fig. A1a, A1b, and A1c). Speed significantly influenced upper thorax left -right lateral flexion at the beginning of the gait cycle (Fig. A1b). Male and female participants presented significant differences in upper thorax flexion-extension at ~38% and ~85% of the gait cycle (Fig. A1a). Neither walking speed nor sex interacted significantly with upper thorax symmetry (Fig. A1a, A1b, and A1c).

Both sexes demonstrated consistent lower thorax flexion-extension, left-right lateral flexion, and left-right rotation throughout both normal and fast overground walking, and the SPM curve remained below the critical threshold $F^* \sim 15$ for adjusted $\alpha = 0.002$ (Fig. A2a, A2b, and A2c). Walking speed notably influenced lower thorax left-right lateral flexion (Fig. A2b) and left-right rotation (Fig. A2c) at various phases of the gait cycle. Notably, men and women showed significant distinctions in lower thorax left-right lateral flexion around 35–45%, 58%, and 85–100% of the gait cycle (Fig. A2b). No significant interactions were noted between walking speed or sex and lower thorax symmetry (Fig. A2a, A2b, and A2c).

Both sexes demonstrated balanced upper lumbar flexion-extension, left-right lateral flexion, and left-right rotation in both normal and fast overground walking, with the SPM curve consistently below the critical threshold $F^* \sim 15$ for adjusted $\alpha = 0.002$ (Fig. A3a, A3b, and A3c). The speed of walking notably affected upper lumbar left-right rotation (Fig. A3c) at different phases of the gait cycle. Men and women showed significant differences in upper lumbar left-right lateral flexion (Fig. A3b) and left-right rotation (Fig. A3c) at various points during the gait cycle. There were no significant interactions observed between walking speed or sex and upper lumbar symmetry (Fig. A3a, A3b, and A3c).

Both female and male participants displayed harmonized lower lumbar flexion-extension, left-right lateral flexion, and left-right rotation during both normal and fast overground walking, with the SPM curve consistently below the critical threshold $F^* \sim 15$ for adjusted $\alpha = 0.002$ (Fig. A4a, A4b, and A4c). Walking speed notably influenced lower lumbar left-right lateral flexion at various phases of the gait cycle (Fig. A4b). Men and women demonstrated noteworthy distinctions in lower lumbar left-right lateral flexion at different points in the gait cycle (Fig. A4b). There were no significant interactions observed between walking speed or sex and lower lumbar symmetry (Fig. A4a, A4b, and A4c).

Both sexes displayed coordinated pelvis posterior-anterior tilt and left-right rotation during both normal and fast overground walking, consistently maintaining the SPM curve below the critical threshold $F^* \sim 15$ for adjusted $\alpha = 0.002$ (Fig. A5a and A5c). However, both genders revealed asymmetry in pelvis left-right obliquity ($p < 0.001$) throughout the entire gait cycle (Fig. A5b). The pace of walking significantly impacted pelvis movements at various phases of the gait cycle (Fig. A5a, A5b, and A5c). Men and women exhibited notable differences in pelvis left-right lateral obliquity at distinct points in the gait cycle (Fig. A5b). No significant interactions were observed between walking speed or sex and pelvis symmetry (Fig. A5a, A5b, and A5c).

Both sexes demonstrated synchronized hip flexion-extension, abduction-adduction, and internal-external rotation throughout both normal and fast overground walking, ensuring that the SPM curve consistently stayed below the critical threshold F*∼15 for adjusted α = 0.002 (Fig. A6a, A6b, and A6c). The pace of walking significantly impacted hip flexion-extension (Fig. A6a) and abduction-adduction (Fig. A6b) at various stages of the gait cycle. Men and women exhibited noticeable variations in hip internal-external rotation at specific points in the gait cycle (Fig. A6c). No significant interactions were noted between walking speed or sex and hip symmetry (Fig. A6a, A6b, and A6c).

Both females and males demonstrated coordinated knee flexion-extension, abduction-adduction, and internal-external rotation in both regular and fast-paced overground walking, ensuring that the SPM curve consistently remained below the critical threshold F*∼15 for adjusted α = 0.002 (Fig. A7a, A7b, and A7c). The walking speed notably influenced knee flexion-extension at different phases of the gait cycle (Fig. A7a). Significant distinctions in knee internal-external rotation were observed between men and women, particularly around ∼55–65% of the gait cycle (Fig. A7c). There were no significant interactions noted between walking speed or sex and knee symmetry (Fig. A7a, A7b, and A7c).

Both sexes displayed coordinated ankle dorsi-plantar flexion, eversion-inversion, and internal-external rotation during both normal and fast overground walking, ensuring that the SPM curve consistently remained below the critical threshold F*∼15 for adjusted α = 0.002 (Fig. A8a, A8b, and A8c). The pace of walking significantly influenced ankle dorsi-plantar flexion (Fig. A8a), eversion-inversion (Fig. A8b), and internal-external rotation (Fig. A8c) at various stages of the gait cycle. Men and women exhibited notable differences in ankle eversion-inversion, particularly around ∼60–90% of the gait cycle (Fig. A8b). No significant interactions were noted between walking speed or sex and ankle symmetry (Fig. A8a, A8b, and A8c).

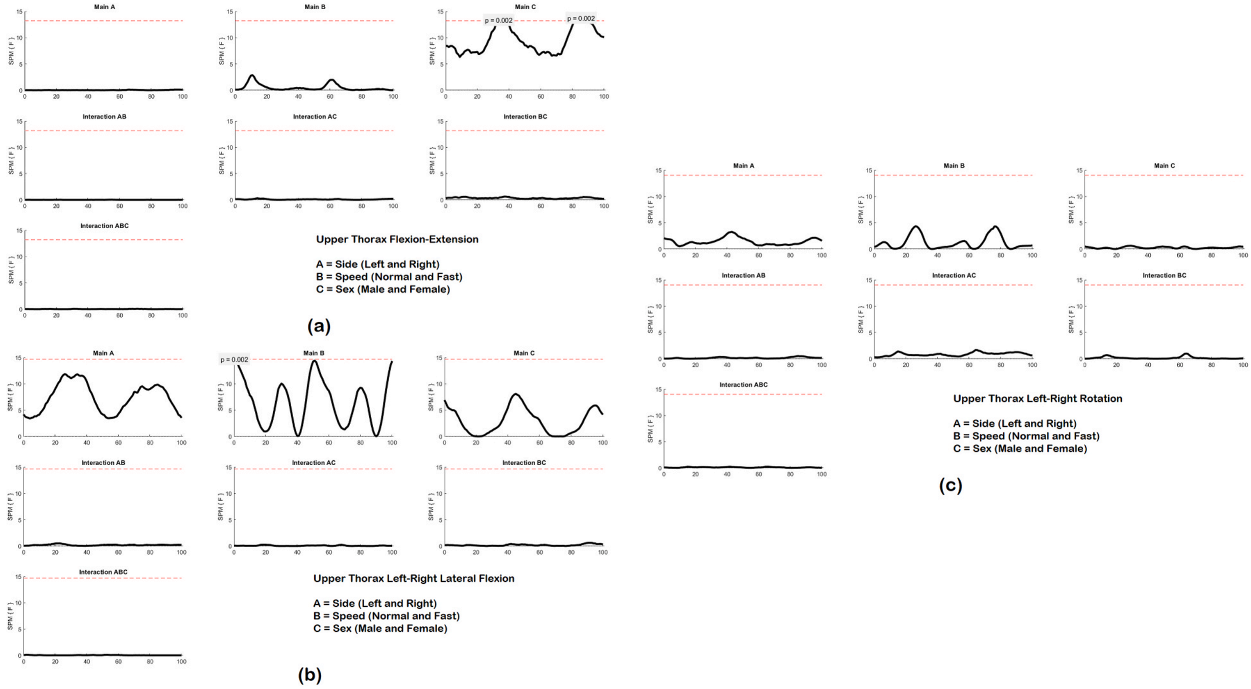


Fig. A1. Results of a three-way ANOVA SPM analysis for upper thorax (a) flexion-extension, (b) left-right lateral flexion, and (c) left-right rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

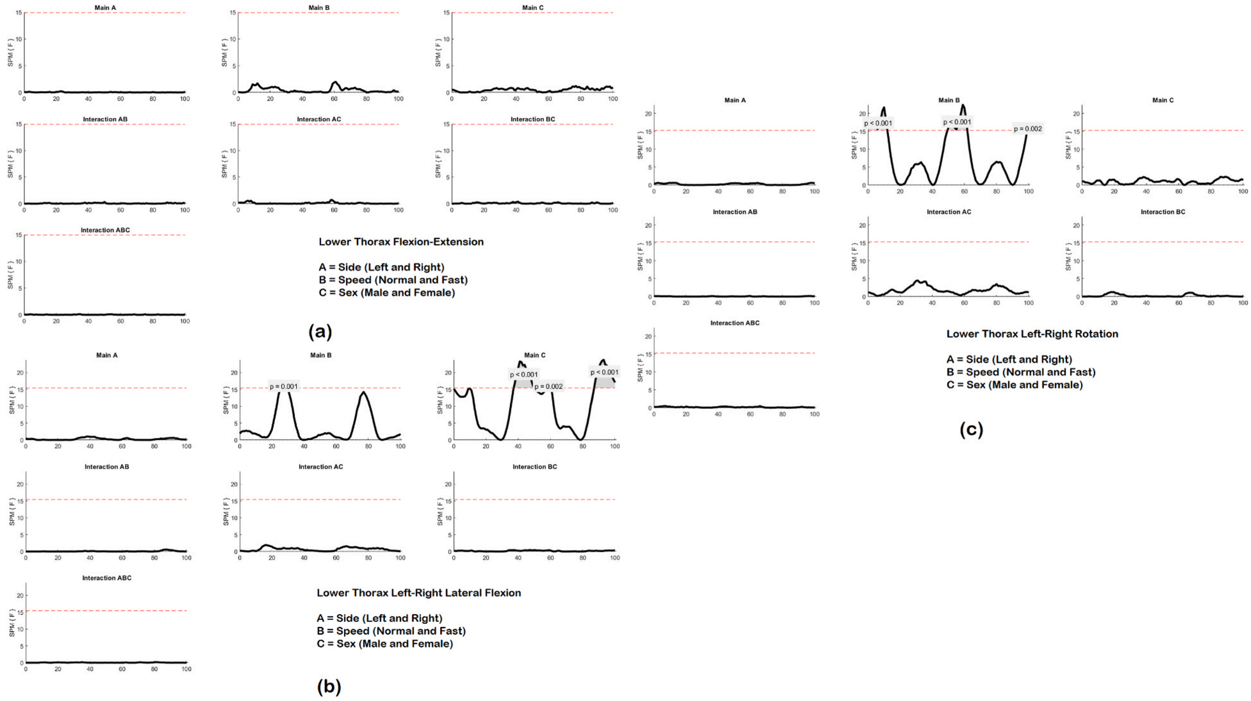


Fig. A2. Results of a three-way ANOVA SPM analysis for lower thorax (a) flexion-extension, (b) left-right lateral flexion, and (c) left-right rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

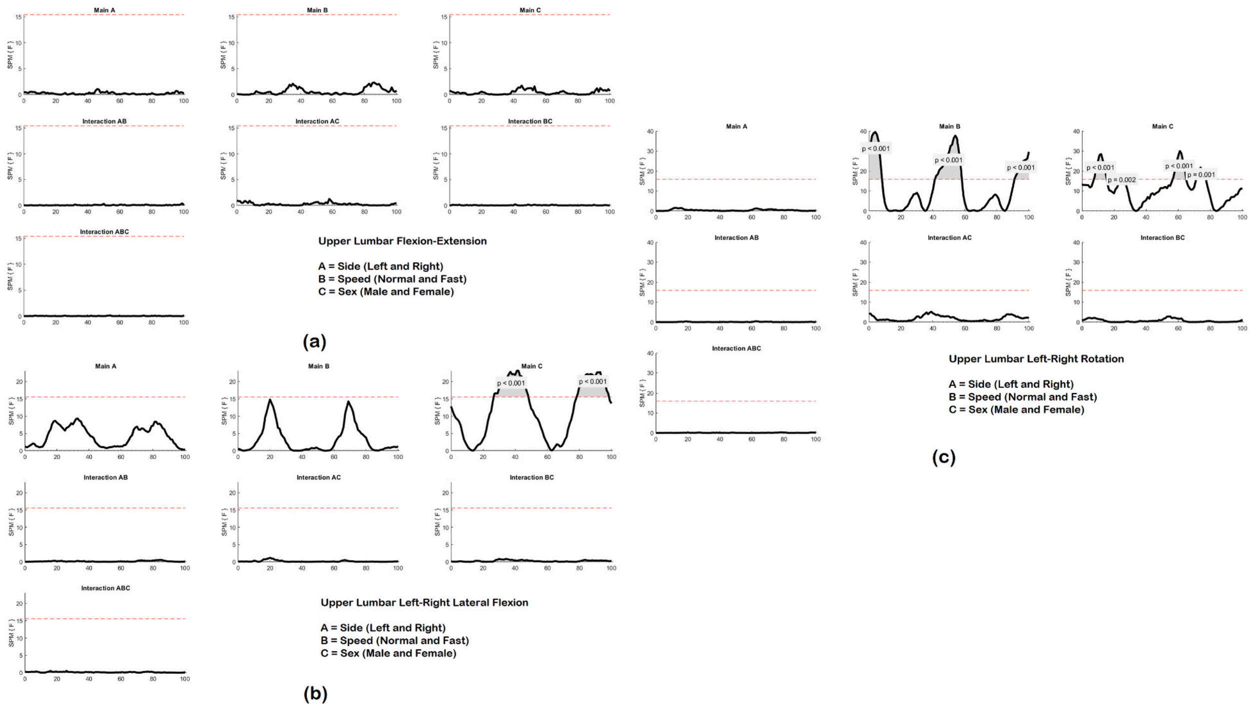


Fig. A3. Results of a three-way ANOVA SPM analysis for upper lumbar (a) flexion-extension, (b) left-right lateral flexion, and (c) left-right rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

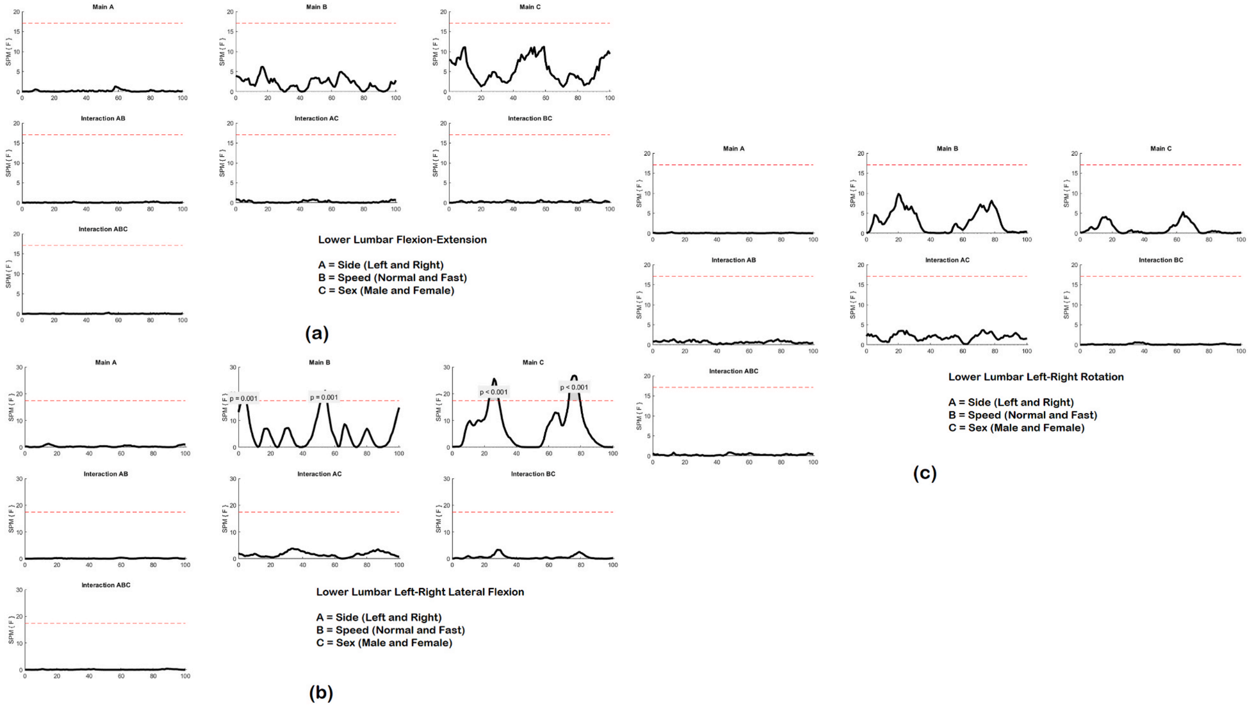


Fig. A4. Results of a three-way ANOVA SPM analysis for lower lumbar (a) flexion-extension, (b) left-right lateral flexion, and (c) left-right rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

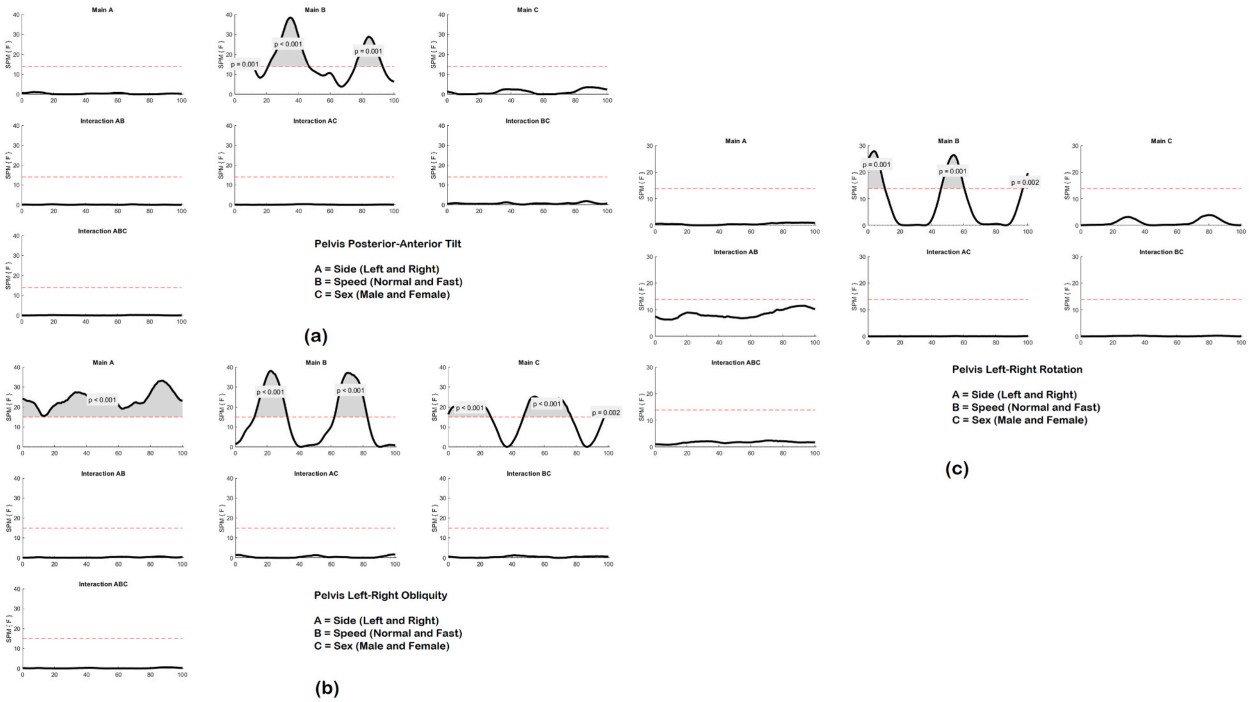


Fig. A5. Results of a three-way ANOVA SPM analysis for pelvis (a) posterior-anterior tilt, (b) left-right obliquity, and (c) left-right rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

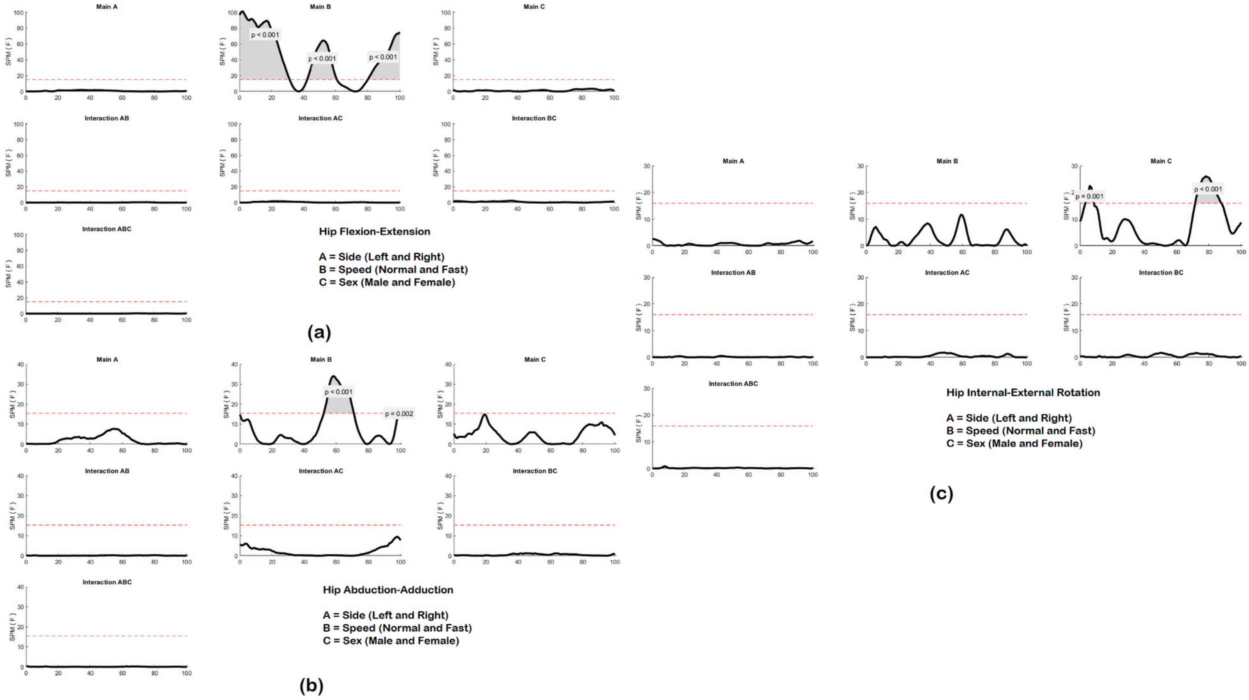


Fig. A6. Results of a three-way ANOVA SPM analysis for hip (a) flexion-extension, (b) adduction-abduction, and (c) internal-external rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

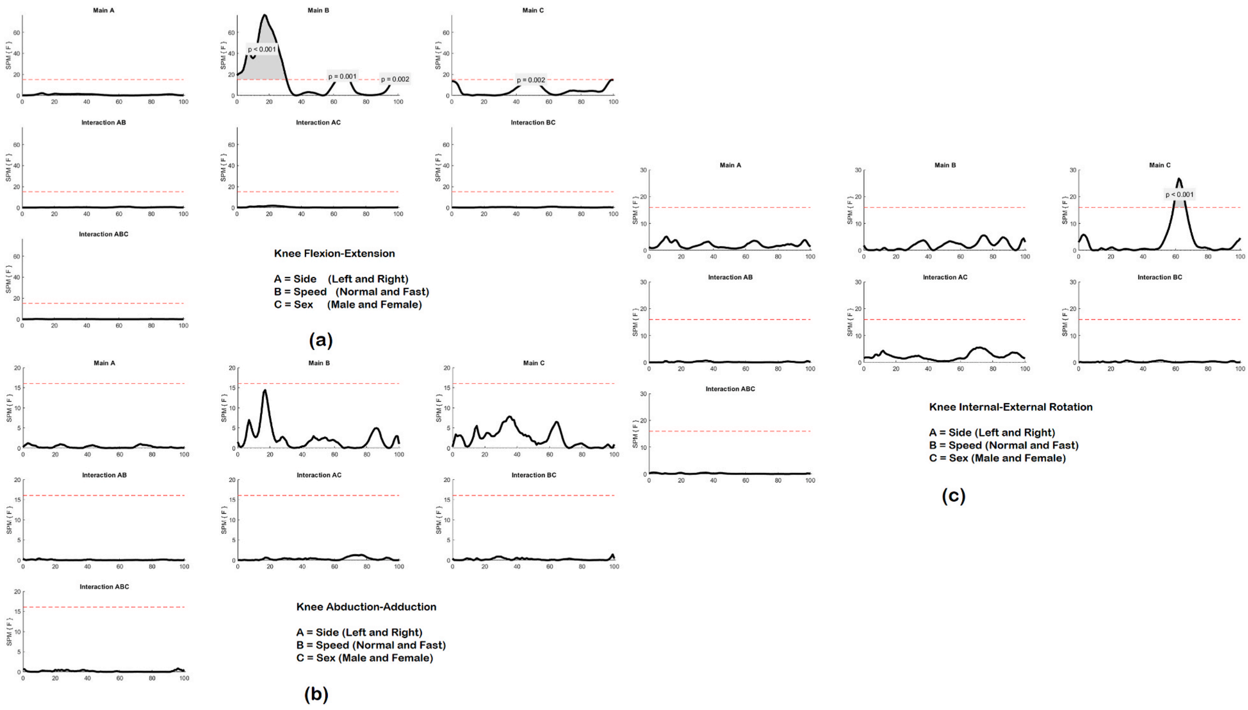


Fig. A7. Results of a three-way ANOVA SPM analysis for knee (a) flexion-extension, (b) adduction-abduction, and (c) internal-external rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicated in gray, and the critical threshold as red dashed line.

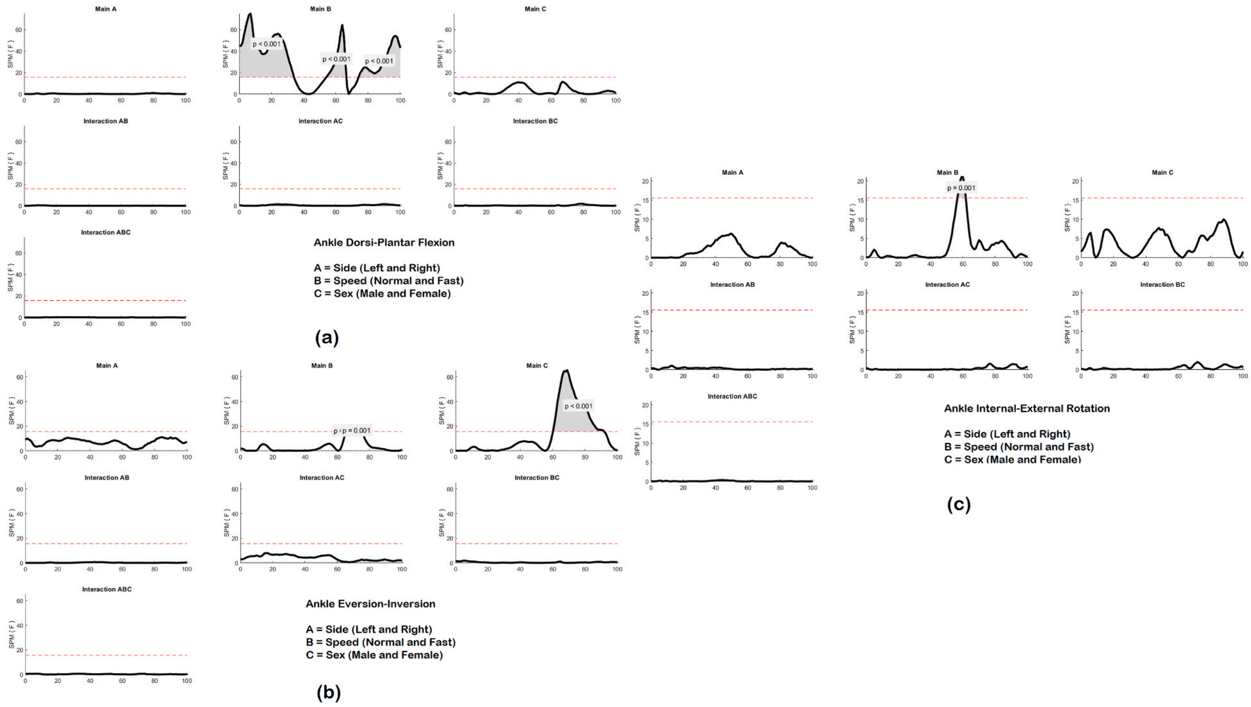


Fig. A8. Results of a three-way ANOVA SPM analysis for ankle (a) dorsi-plantar flexion, (b) eversion-inversion, and (c) internal-external rotation angles during a gait cycle of overground walking. Plots indicate whether there is a statistically significant relationship between each factor: associated side (left vs. right) motion, walking speed (normal vs. fast), and sex (male vs. female), and the response variable: joint angle, along with whether there are any interaction effects between the factors. Supra-thresholds clusters indicating significance difference withing each factor and between factors are indicate.

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