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# Understanding the Center of Pressure Behaviors using Discrete Parameters and Continuous functional Principal Component Analysis

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## Abstract

**Purpose:** Center Of Pressure (COP) is key to understand dynamic stability of Gait Initiation (GI) and Gait Termination (GT). This study investigated the COP between GI and GT from discrete parameters and time-varying coordinates.

**Methods:** Forty healthy male adults participated in this study while walking on a pathway facilitated a Novel EMED pressure plate to record the COP trajectory during the initiation and termination. Discrete parameters of COP duration, velocity, and coordinate deviation were compared, and continuous mediolateral and anteroposterior trajectories were analyzed using SPM1d (one-dimensional Statistical Parametric Mapping) and fPCA (functional Principal Component Analysis).

**Results:** GT with left foot had shorter Forefoot Contact Phase (FFCP) and longer Flatfoot Phase (FFP) than GI, suggesting a quick transition to full-foot support to maintain dynamic stability. COP velocity during Initial Contact Phase (ICP) increased significantly during GT, which may be a strategy to counteract instability. GT also showed larger coordinate deviation during ICP, especially in the mediolateral coordinate, from the SPM analysis. The fPCA further reported the variations of anteroposterior and mediolateral coordinates, serving as the reference of COP profiles for GI and GT analysis in the dominant (right) and non-dominant (left) foot.

**Conclusions:** Knowledge of discrete parameters and continuous coordinates in the COP trajectory from this study may provide implications to reduce inter-limb asymmetry and improve dynamic stability during gait, and may serve as reference to assess gait disorders and rehabilitation.


**Keywords:** Center of Pressure; Gait Stability; Statistical Parametric Mapping; Functional Data Analysis

# 1. Introduction

Center Of Pressure (COP) has been widely investigated to analyze the static balance, postural control, and dynamic stability during gait (Cimolin et al., 2017; Mei et al., 2018; Richmond et al., 2021). Gait Initiation (GI), as a transition from static state to locomotion performed in most daily activities, is not a steady phase as the base of single-leg support becomes narrower than static standing, thus being challenging for balance (Hommen et al., 2024). Contrary to GI, Gait Termination (GT) is a transient period from a dynamic state to static standing (Mortezanejad et al., 2024), which requires the deceleration of forward propulsion via enabling a steady stop (Jeong et al., 2024; Jian et al., 1993). As previously reported, GI and GT require complex interaction between the neuromuscular control and biomechanical coordination to maintain motor balance and dynamic stability (Bechet et al., 2025; Hommen et al., 2024), which is often affected by gait speed (Caderby et al., 2014), obesity (Cau et al., 2014), aging (Hommen et al., 2024), terrain (Vieira et al., 2017), ankle instability (Majlesi, 2025; Mortezanejad et al., 2024), and pathological condition (Cimolin et al., 2017).

The obesity would affect GI stability, showing a higher excursion in the mediolateral COP displacement, reduced progression velocity and longer stance duration (Cau et al., 2014). Longer GI times and shorter first step length were also observed in aging adults with high risks of falling (Hommen et al., 2024). A reduced COP anteroposterior excursion and velocity was found in the ankle instability populations as a strategy to maintain dynamic balance (Mortezanejad et al., 2024) and mediolateral COP displacement was the most sensitive predictor of deficits (Majlesi, 2025). Pathological conditions, such as Parkinson's disease, exhibit larger mediolateral COP velocity and amplitude peak during obstacle crossing, thus affecting the dynamic postural control (Conceição et al., 2019). Concerning GT, a longer duration and reduced COP mediolateral velocity were observed in the obesity populations, which was suggested as strategies to maintain stability, compared to healthy group (Cimolin et al., 2017). Recent studies of GT often involved multi-task, such as GT and prehension to simulate door-open (Jeong et al., 2024), stopping distance during GT (Kimoto et al., 2025), and GT with or without expectation at different speeds in children with cerebral palsy (Kimoto et al., 2024), to understand the complex adaptations for dynamic stability.

However, the above-mentioned studies mainly analyzed the COP as discrete parameters, such as the time (or duration), velocity, and excursion in specific gait phase. The COP trajectory over time, as an instantaneous path between foot and ground, is typically resolved into the mediolateral and anteroposterior coordinates during stance (Mehdizadeh et al., 2021; Mei et al., 2018). Specifically, the discrete metrics of COP excursion, velocity and deviation during sub-phases (such as initial contact, forefoot contact, foot flat and forefoot push-off) were analyzed in traditional approaches (Mei et al., 2015, 2018). Further, due to the continuous time-varying feature of COP trajectories, the one-dimensional Statistical Parametric Mapping (SPM1d), based on topological methodology to detect signals in spatiotemporal continua (Pataky, 2012), was implemented to analyze the vector field statistics of the coordinates during walking stance (Pataky et al., 2014), inclined surface (Vieira et al., 2017), footwear (Willems et al., 2021) to understand the gait behavior. Several advanced approaches, such as extracting key features for prediction of falling risk via machine learning, were proposed (Hernandez-Laredo et al., 2025; Pennone et al., 2024; Quijoux et al., 2021). Further, the DA (Functional Data Analysis) gained popularity in biomechanics because of the applicability to reveal and describe variabilities in the continuous data (Gertheiss et al., 2024; Warmenhoven, 2024). For example, functional Principal Component Analysis (fPCA) could extract variances in ground reaction force (Warmenhoven et al., 2021; Yu et al., 2021) and kinematics during gait (Gunning et al., 2025), identify foot types (Dugan et al., 2024), performance of soccer kicks between sex (Navandar et al., 2022), and detect falling risks in the elderly (Yoshida et al., 2022).

In this study, the authors aimed to conduct comprehensive research of both discrete indices (e.g., velocity, duration, and deviation) and continuous parameters (mediolateral and anteroposterior COP trajectories) during GI and GT. Discrete metrics were examined to facilitate comparisons with existing literature, while continuous parameters were analysed using Statistical Parametric Mapping (SPM) and functional Principal Component Analysis (fPCA) to identify key characteristics of COP trajectories. To the best of our knowledge, this is the first study to analyse COP trajectories during GI and GT separately using fPCA. Furthermore, the study reconstructs the principal sources of variance by identifying time-series regions that explain a high proportion of the observed variability, thereby providing insights into gait instability and fall risk. This approach has the potential to reveal differences in COP behaviour between the dominant and non-dominant limbs during GI and GT beyond conventional statistical inference, thereby enhancing our understanding of dynamic stability and informing gait retraining and rehabilitation strategies.



## 2. Material and methods

### *2.1 Participants*

A total of 40 male participants (age: 32.5±6yrs, height: 174±6.8cm, mass: 70.3±6.5kg, foot length: 253.1±1.8mm) participated in this study. Participants had no history of any lower extremity injuries or functional disorders within the past six months of the gait test, and the right side was the dominant limb as defined from preferred foot of ball-kicking. All participants were informed of the procedures and requirements with written informed consent. The protocol of this study was approved by the ethics committee in the research institute of Ningbo University in accordance with the Declaration of Helsinki (ty2022001).

### *2.2 Experimental protocol*

The experimental protocol is illustrated in **Figure 1**, specifically, participants were asked to get familiar with the testing environment and steps of GI and GT before the study. A Novel EMED pressure mat (Novel GmbH, Munich, Germany) was embedded at the beginning of the 20-m walkway when conducting the GI task with the second step on the pressure plate to achieve a steady-state forward velocity. The GI of the non-dominant and dominant foot were defined as **2L** and **2R**. The pressure mat was mounted at the end of the 20-m walkway to execute the GT task, and the GT of the non-dominant and dominant foot were defined as **20L** and **20R**. To ensure the natural gait performance and avoid step adjustment to target the pressure plate, participants walked at a preferred speed with their eyes looking straight ahead. All tests were performed under barefoot conditions, with successful collection of three trials of COP trajectory from the dominant and non-dominant foot during GI and GT, at a frequency of 50Hz.

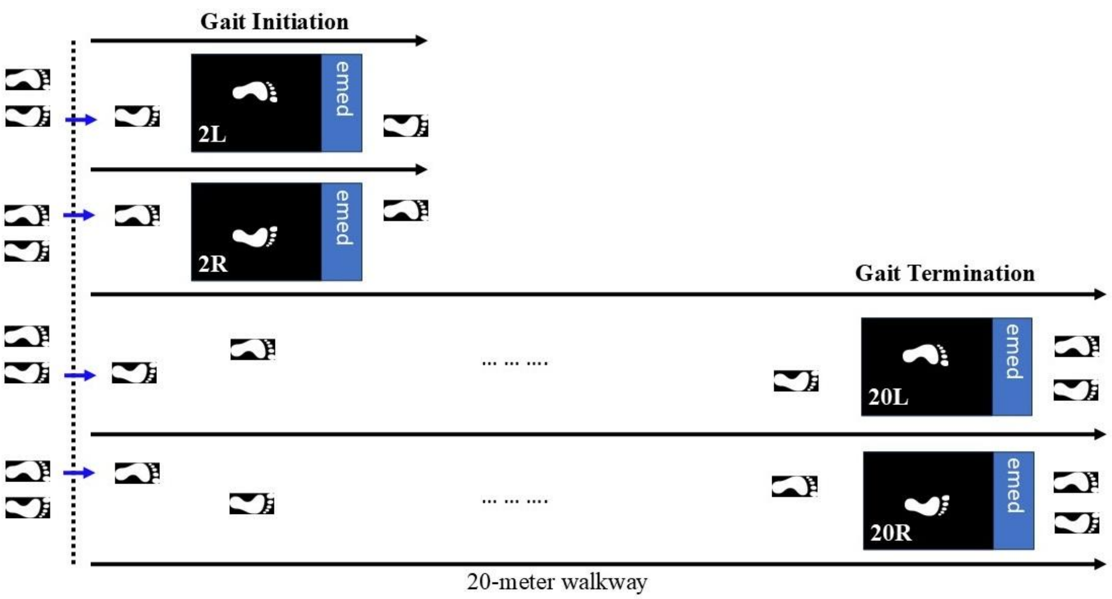



**Figure 1.** Illustration of experimental protocol during gait initiation (GI with non-dominant and dominant foot defined as **2L** and **2R**) and gait termination (GT with non-dominant and dominant foot defined as **20L** and **20R**).

### *2.3 Data processing*

Following the framework reported in our previous studies (De Cock et al., 2008; Mei et al., 2015, 2018), the stance during GI and GT was divided into four sub-phases, Initial Contact Phase (ICP), Forefoot Contact Phase (FFCP), Foot Flat Phase (FFP), and Forefoot Push-Off Phase (FFPOP), separately. The COP trajectory is resolved by coordinates $\boldsymbol{x}$ and $\boldsymbol{y}$, in which $\boldsymbol{x}$ coordinates refer to the anterior-posterior direction, and $\boldsymbol{y}$ coordinates refer to the mediolateral direction.

Further, the COP deviation during different phases was calculated using the **Equation (1)**,

$$\boldsymbol{D_n} = \sqrt{(\boldsymbol{C_{xn}} - \boldsymbol{A_{xn}})^2 + (\boldsymbol{C_{yn}} - \boldsymbol{A_{yn}})^2} \qquad \textbf{(1)}$$

$\boldsymbol{D_n}$ represents the deviation of COP trajectory, $\boldsymbol{C_{xn}}$ and $\boldsymbol{C_{yn}}$ are variables denoting COP trajectory coordinates, and $A_{xn}$ and $A_{yn}$ are average coordinates of COP trajectory, which was previously employed to analyze gait stability during walking (Luximon et al., 2015; Mei et al., 2018). The duration (in percentage) and velocity (in cm/s) of each phase, and the entire COP trajectories were taken into analysis. The initial contact of $\boldsymbol{x}$ and $\boldsymbol{y}$ coordinates was normalized in the anteroposterior ($\boldsymbol{x}$ origin as 0) and mediolateral ($\boldsymbol{y}$ origin as 0) directions, and continuous trajectories were interpolated into 101 data points to represent 100% of stance (Warmenhoven et al., 2021; Yu et al., 2021). The data matrices of 40*101 for the anteroposterior and mediolateral COP trajectories were organized, specifically for the GI of non-dominant and dominant foot and the GT of non-dominant and dominant foot for statistical analysis with SPM and fPCA.

### *2.4 Statistical analysis*

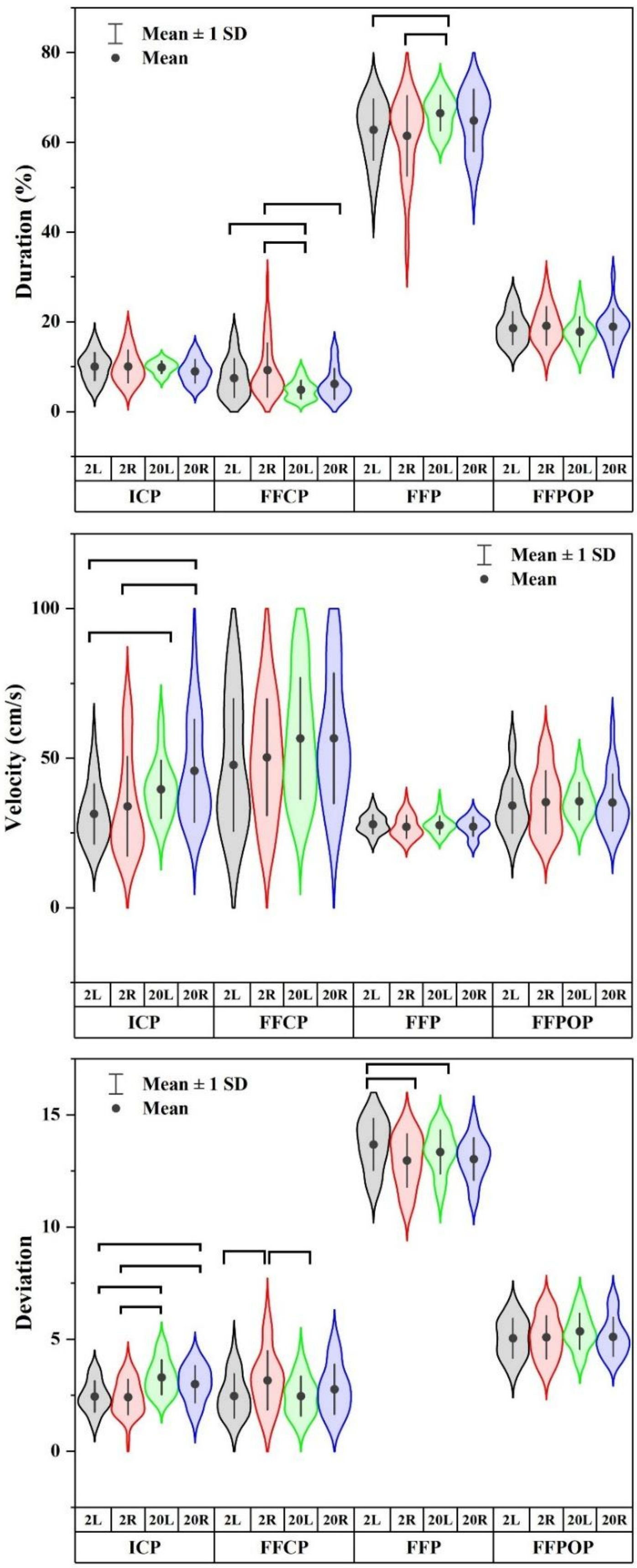
The statistical analysis consisted of two parts, specifically for discrete metrics and continuous parameters. For the analysis of discrete indices, the commonly reported variables in previous studies (Luximon et al., 2015; Mei et al., 2018), separately including COP duration, velocity, and deviation over four phases during GI and GT, were statistically analyzed with repeated-measured ANOVA tests, which were checked with post-hoc Bonferroni pairwise comparisons. Statistical result was highlighted with ***a*** (between 2R and 2L), ***b*** (between 2R and 20R), ***c*** (between 2R and 20L), ***d*** (between 2L and 20L), ***e*** (between 2L and 20R), and ***f*** (between 20R and 20L) with significance. For continuous waveform analysis, time-varying parameters of COP coordinates in the anteroposterior ($\boldsymbol{x}$) and mediolateral ($\boldsymbol{y}$) directions were analyzed with SPM1d to check the significance (Pataky et al., 2014), specifically, an independent t-test for dominant and non-dominant foot and a paired-t test for GI and GT. The significance level was set at 0.05.

To further report the continuous features and main variations in the COP trajectories, the functional Principal Component Analysis (fPCA) was conducted to extract the key variances and the percentage of variance explained (Gertheiss et al., 2024; Warmenhoven, 2024). The first 3PCs with accumulated variances of 90% were extracted and reconstructed in the anteroposterior and mediolateral COP trajectories to show the alterations between GI and GT. The '***fda***' package in R Archive Network was employed in the fPCA and plot the fPCs using Rstudio statistics software (v2025.05.0, +496). The fPC1 versus fPC2 plot are presented in the ***Appendix***.

# 3. Result

### *3.1 Comparison of discrete COP parameters in the dominant and non-dominant foot between GI and GT*

The descriptive analysis of COP parameters in the dominant and non-dominant foot during GI and GT are presented with mean, standard deviation, 95% confidence interval, specifically statistics for the duration, velocity, deviation (**Figure 2**).

189 


190 **Figure 2.** Statistics of COP duration, velocity, and deviation in sub-phases during GI and GT.

In **Table 1**, no significance was detected in the COP duration during the ICP of GI and GT in dominant and non-dominant foot, while the GI of dominant foot exhibits longer duration than GT of dominant and non-dominant foot ($p<0.05$), and GI of non-dominant foot shows longer duration than GT of non-dominant ($p<0.05$) during the FFCP. In the FFP, both GI of dominant and non-dominant foot are shorter than GT of non-dominant foot ($p<0.05$).

**Table 1.** Statistical analysis of COP duration (unit: % stance) during GI and GT

| | | GI | | GT | |
|---|---|---|---|---|---|
| | | Mean±SD | 95%CI | Mean±SD | 95%CI |
| ICP | Dominant | 10.08±3.64 | 2.18-2.68 | 9.0±2.61 | 2.74-3.27 |
| | Non-dominant | 10.06±3.15 | 2.23-2.68 | 9.9±1.43 | 3.06-3.56 |
| FFCP | Dominant | **9.28±5.98** $^{b,c}$ | 2.75-3.59 | **6.21±3.44** $^{b}$ | 2.42-3.13 |
| | Non-dominant | **7.49±4.26** $^{d}$ | 2.16-2.79 | **4.9±0.89** $^{c,d}$ | 2.18-2.76 |
| FFP | Dominant | **61.51±8.92** $^{c}$ | 12.59-13.35 | 64.9±6.93 | 12.74-13.34 |
| | Non-dominant | **62.84±6.77** $^{d}$ | 13.32-14.05 | **66.54±3.9** $^{c,d}$ | 13.04-13.66 |
| FFPOP | Dominant | 19.13±4.23 | 4.79-5.4 | 18.93±4.04 | 4.84-5.39 |
| | Non-dominant | 18.64±3.62 | 4.77-5.33 | 17.85±3.32 | 5.1-5.61 |

Notes: GI-Gait Initiation; GT-Gait Termination; SD-Standard Deviation; 95%CI-95% Confidence Interval; ICP-Initial Contact Phase; FFCP-Forefoot Contact Phase; FFP-Foot Flat Phase; FFPOP-Forefoot Push Off Phase. Statistics with significance was highlighted with ***a*** (between 2R and 2L), ***b*** (between 2R and 20R), ***c*** (between 2R and 20L), ***d*** (between 2L and 20L), ***e*** (between 2L and 20R), and ***f*** (between 20R and 20L).

In **Table 2** of the COP progression velocity, significance is observed during the ICP, specifically, GI of non-dominant foot is slower than GT of the dominant and non-dominant foot ($p<0.05$). GI of dominant foot is slower than GT of dominant foot ($p<0.05$). In **Table 3**, the COP deviation during

ICP shows significance between GI of non-dominant foot and GT of non-dominant foot ($p<0.05$), GI of dominant foot and GT of non-dominant foot ($p<0.05$), GI of non-dominant foot and GT of dominant foot ($p<0.05$), and GI of dominant foot and GT of non-dominant foot ($p<0.05$). During FFCP, the GI of non-dominant foot was statistically smaller than GI of dominant foot ($p<0.05$). The GI of dominant foot was larger than GT of non-dominant foot ($p<0.05$). During FFP, the GI of dominant foot was smaller than the GI of dominant foot ($p<0.05$) and non-dominant foot ($p<0.05$), respectively.

**Table 2.** Statistical analysis of COP velocity (unit: cm/s) during GI and GT

| | | GI | | GT | |
|---|---|---|---|---|---|
| | | Mean±SD | 95%CI | Mean±SD | 95%CI |
| ICP | Dominant | **33.91±16.59** [b] | 28.6-39.22 | **45.81±17.14** [b,e] | 36.5-42.7 |
| | Non-dominant | **31.35±10.05** [d,e] | 28.13-34.56 | **39.6±9.7** [d] | 36.5-42.7 |
| FFCP | Dominant | 51.81±23.15 | 44.4-54.84 | 56.67±21.8 | 49.69-63.6 |
| | Non-dominant | 47.77±22.11 | 40.7-54.84 | 56.63±20.3 | 50.15-63.11 |
| FFP | Dominant | 27.08±3.77 | 25.88-28.29 | 27.11±3.2 | 26.08-28.13 |
| | Non-dominant | 27.93±3.18 | 26.92-28.95 | 27.61±3.0 | 26.65-28.57 |
| FFPOP | Dominant | 35.3±10.45 | 31.95-38.64 | 35.21±9.5 | 32.17-38.25 |
| | Non-dominant | 34.18±9.17 | 31.25-37.11 | 35.63±6.2 | 33.65-37.61 |

Notes: GI-Gait Initiation; GT-Gait Termination; SD-Standard Deviation; 95%CI-95% Confidence Interval; ICP-Initial Contact Phase; FFCP-Forefoot Contact Phase; FFP-Foot Flat Phase; FFPOP-Forefoot Push Off Phase. Statistics with significance was highlighted with ***a*** (between 2R and 2L), ***b*** (between 2R and 20R), ***c*** (between 2R and 20L), ***d*** (between 2L and 20L), ***e*** (between 2L and 20R), and ***f*** (between 20R and 20L).

**Table 3.** Statistical analysis of COP deviation (unitless) during GI and GT

| | | GI | | GT | |
|---|---|---|---|---|---|
| | | Mean±SD | 95%CI | Mean±SD | 95%CI |
| ICP | Dominant | **2.42±0.78** $^{b,c}$ | 2.18-2.68 | **3.0±0.82** $^{b,e}$ | 2.74-3.27 |
| | Non-dominant | **2.45±0.7** $^{d,e}$ | 2.23-2.68 | **3.31±0.78** $^{c,d}$ | 3.06-3.56 |
| FFCP | Dominant | **3.17±1.32** $^{a,c}$ | 2.75-3.59 | 2.78±1.11 | 2.42-3.13 |
| | Non-dominant | **2.48±0.98** $^{a}$ | 2.16-2.79 | **2.47±0.89** $^{c}$ | 2.18-2.76 |
| FFP | Dominant | **12.97±1.18** $^{a}$ | 12.59-13.35 | 13.04±0.95 | 12.74-13.34 |
| | Non-dominant | **13.69±1.15** $^{a,d}$ | 13.32-14.05 | **13.35±0.97** $^{d}$ | 13.04-13.66 |
| FFPOP | Dominant | 5.09±0.96 | 4.79-5.4 | 5.11±0.86 | 4.84-5.39 |
| | Non-dominant | 5.05±0.88 | 4.77-5.33 | 5.36±0.8 | 5.1-5.61 |

Notes: GI-Gait Initiation; GT-Gait Termination; SD-Standard Deviation; 95%CI-95% Confidence Interval; ICP-Initial Contact Phase; FFCP-Forefoot Contact Phase; FFP-Foot Flat Phase; FFPOP-Forefoot Push Off Phase. Statistics with significance was highlighted with ***a*** (between 2R and 2L), ***b*** (between 2R and 20R), ***c*** (between 2R and 20L), ***d*** (between 2L and 20L), ***e*** (between 2L and 20R), and ***f*** (between 20R and 20L).

### *3.2 Comparison of COP trajectories in the dominant and non-dominant foot between GI and GT*

The significance of mediolateral COP between the non-dominant foot and dominant foot was found in GI, during 78-100% ($p<0.001$) of the FFPOP (**Figure 3**), with a significantly medially deviated trajectory in the dominant foot. While comparing the GI and GT of non-dominant foot, significance was observed during 10-28% ($p<0.001$) and 37-38% ($p<0.001$) in the mediolateral COP (medially deviated in the GT) and during 11-16% ($p<0.001$) in the anteroposterior COP (anteriorly shifted in GT) (**Figure 4**). No significant different were found in the statistical analysis of other continuous trajectories.

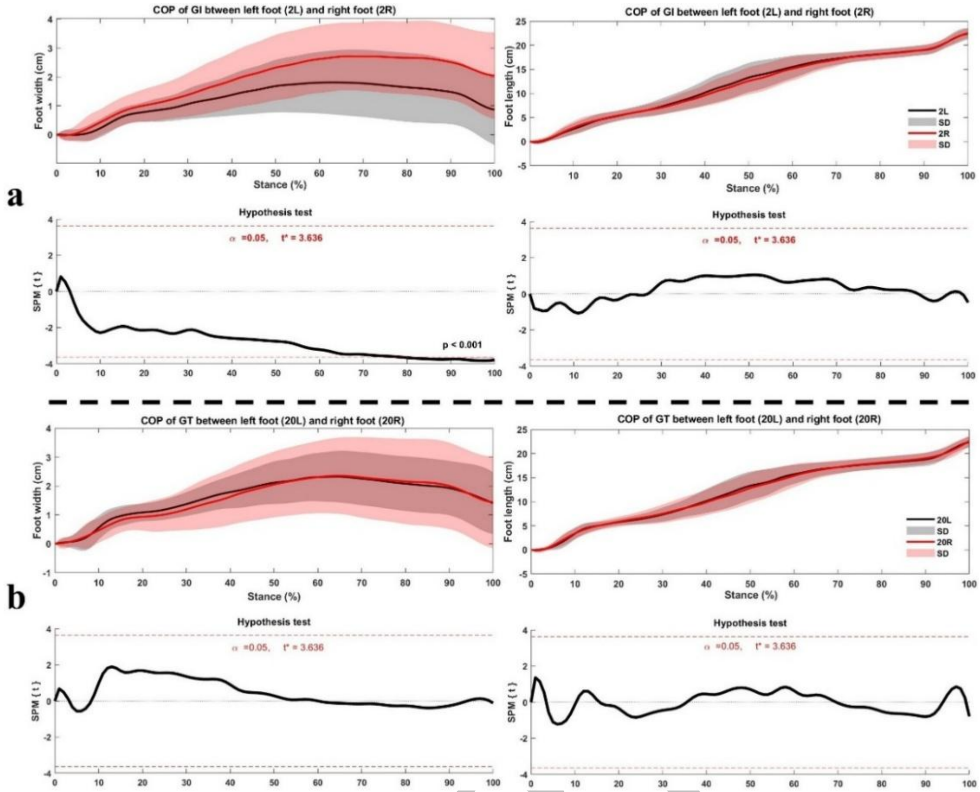



**Figure 3.** Statistics of COP between non-dominant and dominant foot during GI (**a**) and GT (**b**). The positive indicates medial direction (mediolateral trajectory) and anterior direction (anteroposterior trajectory).

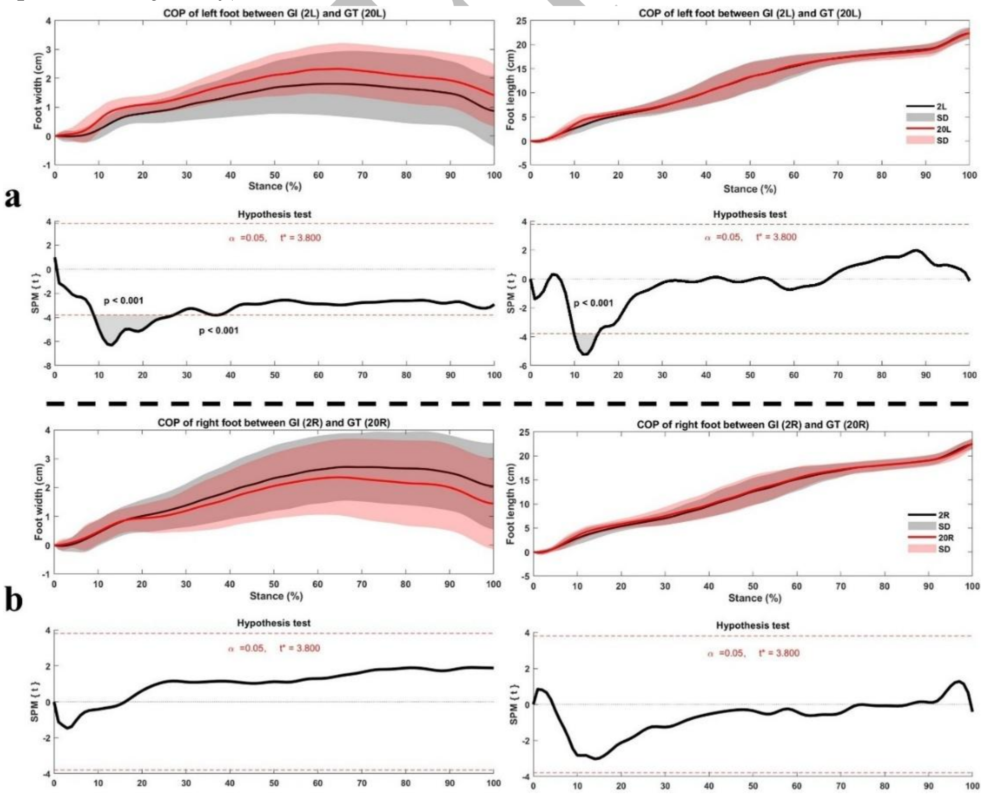



**Figure 4.** Statistics of COP in non-dominant (**a**) and dominant (**b**) foot between GI and GT. The positive indicates medial direction (mediolateral trajectory) and anterior direction (anteroposterior trajectory).

### *3.3 Functional Principal Component Analysis (fPCA) of COP trajectories*

Following the fPCA of the anteroposterior COP trajectories of non-dominant and dominant stance during GI and GT (**Figure 5**), the fPC1 shows variances of 80% (non-dominant) and 70% (dominant) during GI and variances of 80% (non-dominant) and 80% (dominant) during GT, especially during 20-80% of stance in the non-dominant and 25-75% of stance in the dominant, with greatest variations during mid-stance (50%). While fPC2 shows a variance of 13% (non-dominant) and 11% (dominant) during GI, the negative phase surpasses the positive phase in the second half of stance. The fPC2 of GT has a variance of 7% in non-dominant stance and 9% in dominant stance, showing smaller magnitude of COP variations compared to GI. The fPC3 presents a variance of 5% (non-dominant) and 9.6% (dominant) during GI, and 5.6% (non-dominant) and 4.5% (dominant) during GT, with smaller variations observed during GT.

In terms of the fPCA of the mediolateral COP trajectories of non-dominant and dominant stance during GI and GT (**Figure 6**), the fPC1 shows variances of 90% (non-dominant) and 80% (dominant) during GI and variances of 90% (non-dominant) and 90% (dominant) during GT, especially from 25% till push-off. The fPC2 exhibits variance of 6% (non-dominant) and 11% (dominant) during GI and variance of 7% (non-dominant) and 5% (dominant) during GT, with the negative surpass positive COP from 60% till push-off. The fPC3 has variance of 2.5% in non-dominant and 3.5% in dominant foot during GI, and 2.8% (non-dominant) and 1.4% (dominant) during GT. The magnitude of COP variations is smaller in the fPC2 and fPC3 compared with fPC1.

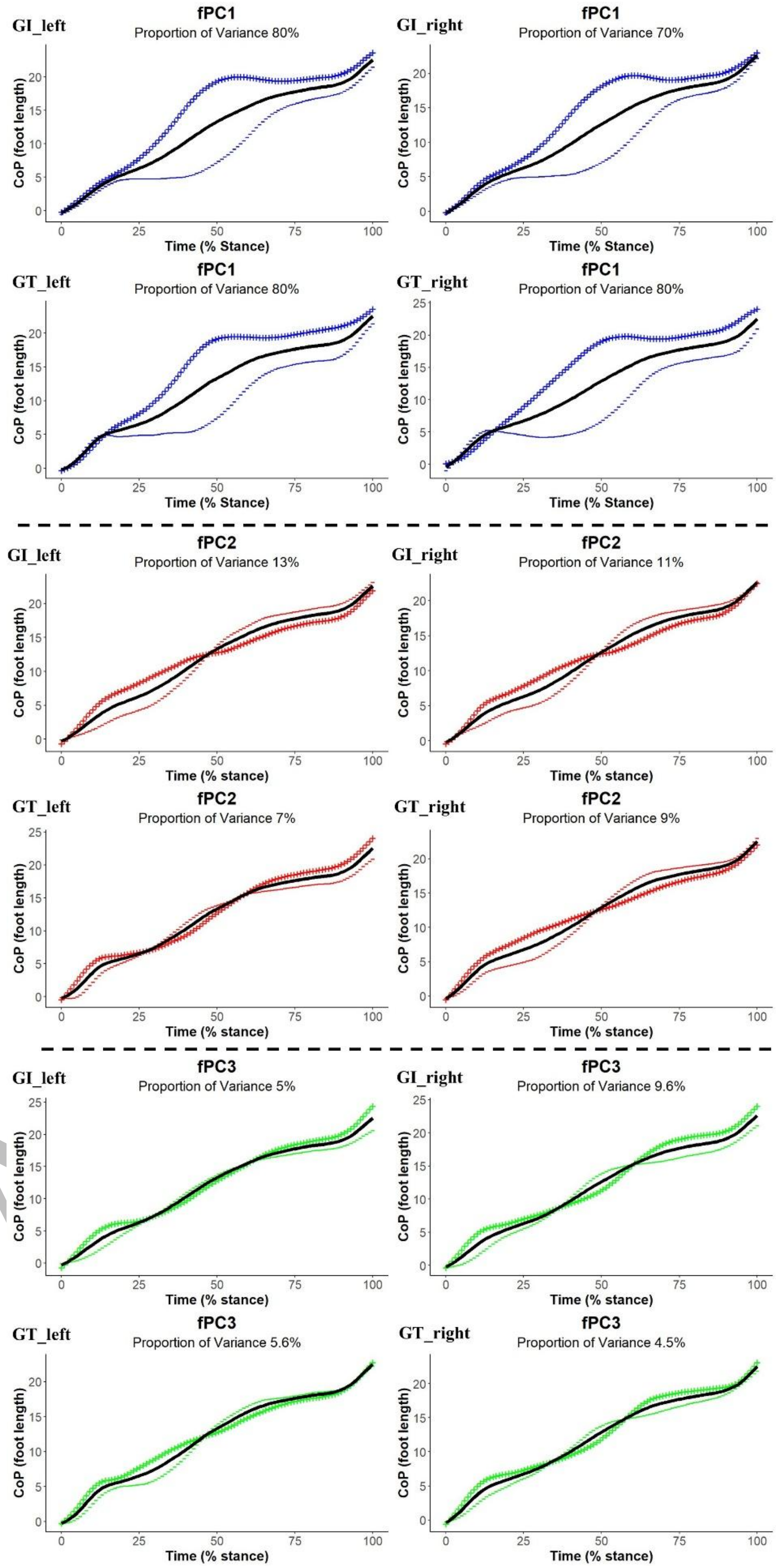



**Figure 5.** Statistics of anteroposterior (AP) COP in non-dominant foot and dominant foot during GI and GT with reconstructed mean and 2SD (positive in '+' and negative in '-') in blue for fPC1, red for fPC2 and green for fPC3.

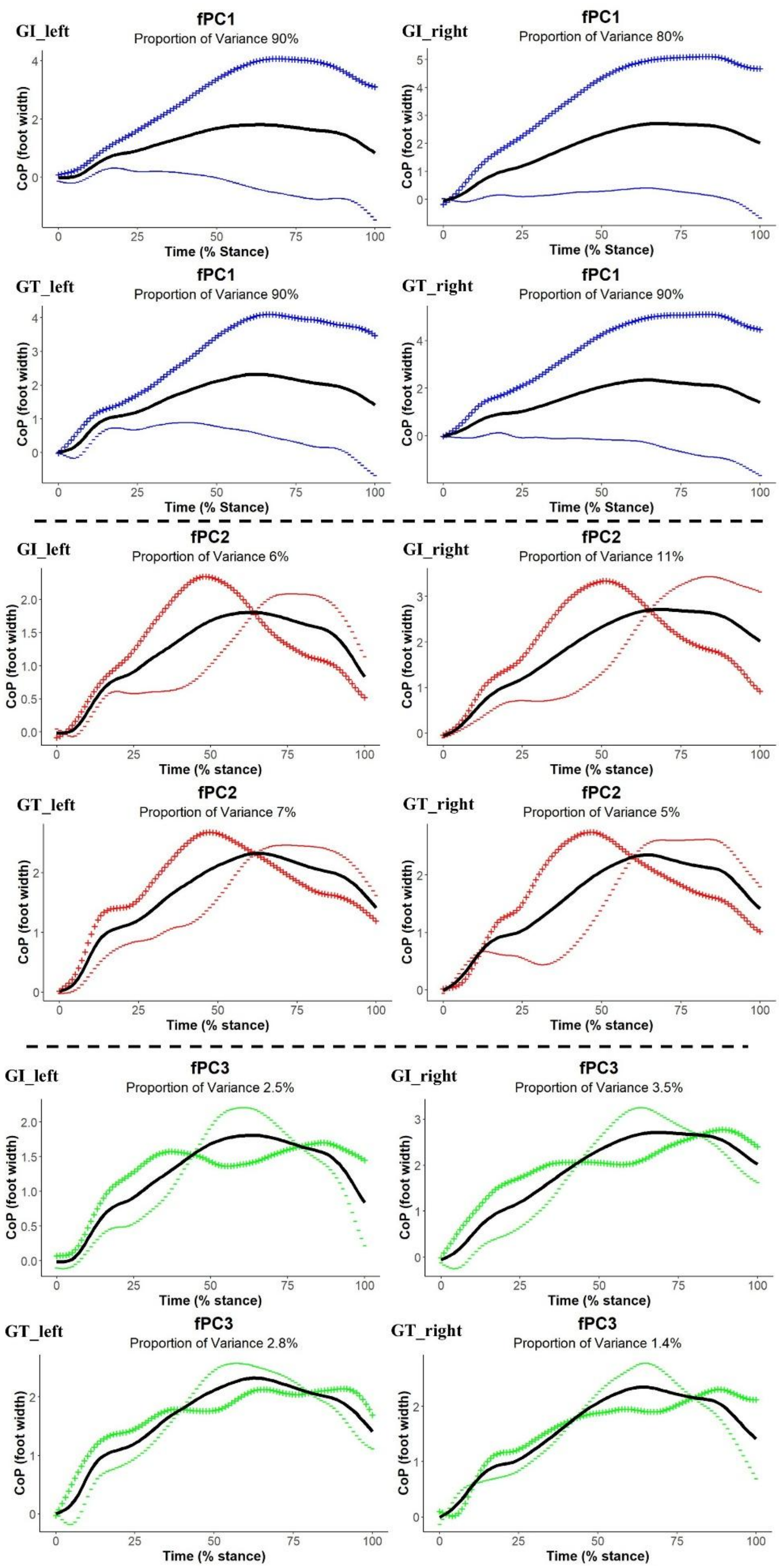



**Figure 6.** Statistics of mediolateral (ML) COP in non-dominant foot and dominant foot during GI and GT with reconstructed mean and 2SD (positive in '+' and negative in '-') in blue for fPC1, red for fPC2 and green for fPC3.

# 4. Discussion

COP reflects the instantaneous position of the foot-ground contact, which could be informative for static balance and dynamic stability (Mehdizadeh et al., 2021; Richmond et al., 2021). This study provided a comprehensive understanding of the COP trajectory during GI and GT via integrated analysis of discrete indices and continuous trajectories. From the best of our knowledge, this study was the first in the literature to treat mediolateral and anteroposterior coordinates as a function for fPCA to extract variances between GI and GT between the non-dominant and dominant stance, as COP profiles to evaluate dynamic postural control. Considering the limited sample of males, the findings may not be applicable to female participants. While combing the results of discrete variables and PC variations, the findings from the current study may provide implications to reduce inter-limb asymmetry and improve gait stability during GI and GT, further serving as a reference to assess gait disorders and rehabilitation.

Temporal metrics, such as duration and velocity of COP during foot roll-over locomotion via plantar pressure analysis (Ramirez-Bautista et al., 2018), is important to understand the stance strategy and gait balance (Caderby et al., 2014; Jeong et al., 2024; Mei et al., 2018; Richmond et al., 2021). While integrating the COP sub-phase with gait cycle, the ICP and FFCP are linked with the loading response, the FFP is linked with mid-stance, and the FFPOP is related to the terminal stance and pre-swing during gait (Shah et al., 2020). Concerning the duration between sub-phases, a significant decrease of duration was observed in the FFCP of GT compared to GI in both non-dominant and dominant stance, which is consistent with the finding of shorter GT time (Kimoto et al., 2025). The reduced duration of FFCP during GT may suggest a quick transition from first metatarsal contact to all metatarsals contact, which may link with the employment of full-foot (midfoot strike) support (ankle plantarflexion and subtalar pronation) to maintain dynamic balance (Molina et al., 2023). Furthermore, the dominant foot had a longer duration than the non-dominant foot during GI and GT separately, suggesting that the dominant limb show a stable landing pattern against the non-dominant limb with quick sub-phase transition (Paillard & Noé, 2020). In terms of the FFP (indicator of mid-stance), the duration of GT during non-dominant stance was longer than the GI of non-dominant stance and dominant stance, suggesting the non-dominant limb may require extra time to prepare for push-off, which is linked with longer re-stabilization time (Paillard & Noé, 2020). The findings suggest that gait termination with non-dominant foot may have higher risks of gait instability, and the altered strategy reported in the current study might be reference for gait retraining to improve dynamic balance control.

The COP velocity in the heel and midfoot regions are associated with gait velocity, especially the COP velocity in midfoot area (Fuchioka et al., 2015). In this study, the ICP velocity increased significantly during GT of dominant and non-dominant stance compared to the GI, which is during the double support phase that the front foot lands with heel while the rear foot is the forefoot push-off, a key period of gait dynamic stability (Shah et al., 2020; van den Bogaart et al., 2020). The quick transition of ICP during GT to FFCP and FFP, consistent with shorter duration, was achieved by higher velocity due to the magnitude of acceleration (Masani et al., 2014), suggesting as a potential indicator of dynamic postural instability during loading response (Shah et al., 2020). These alterations of COP velocity could be documented as gait profiles that shall be noted for dynamic stability, as a description of foot behavior added to the current COP profiles, apart from the existing report of the metatarsophalangeal joint osteoarthritis (Menz et al., 2018), elderly adults (Chiu et al., 2013), and pregnant females (Mei et al., 2018).

COP trajectory, due to the time-varying characteristics, could reflect certain features while analyzing gait behavior and plantar loading profile, as resolved into the mediolateral and anteroposterior coordinates (Mehdizadeh et al., 2021). Previous studies have employed deviation to report stance stability during the waking gait in high-heel shoes (Luximon et al., 2015) and pregnancy (Mei et al., 2018), with higher deviation value indicating decreased stability. In the current study, the ICP deviation value during GI was smaller than the deviation during GT in both the dominant and non-dominant stance, separately, suggesting decreased stability during loading response and weight transfer of GT (Howcroft et al., 2016; Luximon et al., 2015; Yiou et al., 2017). While during the FFCP, the deviation of dominant stance was larger than non-dominant stance, which may be due to the strategy employed to maintain dynamic stability with initial metatarsal contact, as a key influence of limb dominance on postural control (Paillard & Noé, 2020). During the transition into the FFP, the higher deviation during mid-stance may be a strategy to compensate the instability (Luximon et al., 2015).

Vector statistics, such as Statistical Parametric Mapping, has been successfully employed to understand the variations of time-varying COP coordinates during stance (Pataky et al., 2014).

During the GI, a medially shifted COP was observed in the dominant foot, especially during the late stance (78-100%), which may be due to the significant contribution of the first metatarsophalangeal joint to assist the push off (Sole et al., 2017). The difference is also consistent with findings of discrete parameter that the COP velocity of the dominant foot during the FFPOP is higher than non-dominant foot during GI, suggesting quick transition of the forefoot push-off (Wager & Challis, 2024). While comparing the COP path between GI and GT during stance, significance was observed in the non-dominant foot, specifically during ICP and FFCP, the more medially deviated COP may indicate a strategy of pronated foot posture to maintain dynamic stability during gait termination in the non-dominant limb (**20L**) (Mousavi et al., 2024). Furthermore, the more anteriorly shifted COP may suggest the quick transition to the full-foot support (mid-stance) for postural balance (Paillard et al., 2025), which is consistent with shorter duration as observed in the discrete parameters. However, these alterations between GI and GT were not reported in the dominant limb, suggesting that the non-dominant limb may adopt a different strategy, such as a medially transited and anteriorly shifted COP trajectory, to maintain dynamic gait stability in this study (Alomar et al., 2023; Paillard & Noé, 2020).

In this study, the fPCA of the COP coordinate showed promising validity as this approach was successfully employed to analyze GRF (Warmenhoven et al., 2021), running kinematics (Gunning et al., 2025), and foot kinematics (Dugan et al., 2024). As findings of the current study indicated, both dominant and non-dominant limbs showed similar variations in the fPC1 (70-80% variances) of anteroposterior trajectory with the main variability observed during 20%~80% of stance. In the fPC2 (7-13%), the GI had similar patterns of variations between non-dominant and dominant limb, with anteriorly shifted COP during the first half of stance but posteriorly shifted was found in the second half of stance. However, during GT, the dominant foot had consistent COP coordinate path with GI while the non-dominant foot showed large alterations in the reconstructed coordinate path. These variations linked with the statistical significance found in the discrete parameters and SPM analysis during ICP and FFCP, which may suggest the primary strategy employed for postural control and dynamic stability (Mousavi et al., 2024; Paillard et al., 2025). In the fPC3 (4.5-9.6%), the non-dominant foot showed a similar pattern of variations between GI and GT during early stance, while dominant foot had similar variation pattern, but GT had smaller percentage of variations. This finding of reduced variation percentage may suggest a stable gait termination in the dominant limb, as consistent with other fPCA of biomechanical studies (Dugan et al., 2024; Warmenhoven et al., 2021; Yoshida et al., 2022), whilst the anteroposterior COP coordinates may be noted as a strategy to maintain balance during GI and GT. As for the mediolateral COP coordinates, the main variations of the medially deviated path were noted in the fPC1 (80-90%), which was previously reported as a strategy of active foot pronation and first metatarsophalangeal joint work to assist push off (Sole et al., 2017; Wager & Challis, 2024). A similar medial to lateral transition of COP coordinate was observed in the fPC2 (5-11%) around 60% of stance that the medially shifted COP path showed lateral transition. In the fPC3 (1.4-3.5%), the fluctuation of medial-lateral shift coordinates around 45% to 75%, which is around mid-stance phase, may implicate as a strategy of ankle plantarflexion and subtalar pronation to reach full foot contact for balance maintenance (Alomar et al., 2023; Lugade & Kaufman, 2014; van den Bogaart et al., 2020).

Several limitations should be considered before acknowledging findings from this study. Firstly, the current study mainly involved healthy male adults without analyzing other cohorts, such as females, the elderly and populations with foot and ankle disorders. Future studies shall recruit a larger sample with participants of both sex, different health conditions and age categories. Secondly, this study mainly analyzed the COP trajectory-related discrete parameters and coordinate path, although a comprehensive kinematic and kinetic analysis, and muscle activities from surface electromyography may offer extra insights about the neuromuscular control of dynamic gait stability. However, this study still provided strong evidence and a comprehensive profile concerning the differences between GI and GT in non-dominant and dominant limbs.

## 5. Conclusions

This study presented a comprehensive understanding of the COP profiles during GI and GT between the dominant and non-dominant foot via analysis of discrete parameters and continuous coordinates. GT of non-dominant foot had shorter FFCP and longer FFP than GI, suggesting a quick transition to full-foot support, which might suggest the maintenance of dynamic stability. The significantly increased COP velocity and larger deviation of mediolateral coordinate during ICP may be a strategy to counteract instability. Variations of anteroposterior and mediolateral coordinates from fPCA could serve as the reference of COP profiles for GI and GT analysis in the dominant and non-dominant foot. Knowledge of discrete parameters and continuous coordinates in the COP trajectory from this study may provide implications to reduce inter-limb asymmetry during gait, and may serve as a reference to assess gait disorders and rehabilitation.

## List of abbreviations

AP – Anteroposterior

COM – Center of Mass

COP – Center of Pressure

FDA – Functional Data Analysis

fPCA – Functional Principal Component Analysis

FFCP - Forefoot Contact Phase

FFP - Foot Flat Phase

FFPOP - Forefoot Push-off Phase

GI – Gait Initiation

GT – Gait Termination

ICP - Initial Contact Phase

ML – Mediolateral

2L – Gait Initiation of Non-dominant Step

2R – Gait Initiation of Dominant Step

20L – Gait Termination of Non-dominant Step

20R – Gait Termination of Dominant Step

# Declarations

## Ethics approval and consent to participate:

The protocol of this study was approved by the ethics committee in the research institute of Ningbo University (ty2022001). All participants were informed of the procedures and requirements with written informed consent.

## Consent for publication:

Not applicable.

## Availability of data and materials:

Data contributing findings of this study are available from the project online repository (doi: 10.17608/k6.auckland.29390987).

## Competing interests:

Authors declare no competing interests.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## CRediT authorship contribution statement:

**Qichang Mei:** Conceptualization, Formal analysis, Methodology, Software, Supervision, Validation, and Writing - original draft; **Yuming Wang:** Data curation, Investigation, Methodology, Validation, Visualization, and Writing - original draft; **Chen Liu:** Investigation, Software, Validation, Visualization; **Xiaoyi Yang:** Data curation, Investigation, Validation, and Writing - original draft; **Junjie Fang**: Conceptualization, Methodology, Validation, Writing-review & editing; **Bernard XW Liew:** Validation and Writing - review & editing; **Yaodong Gu:** Funding acquisition, Project administration, Resources, Supervision, Validation, and Writing - review & editing.


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# Appendix

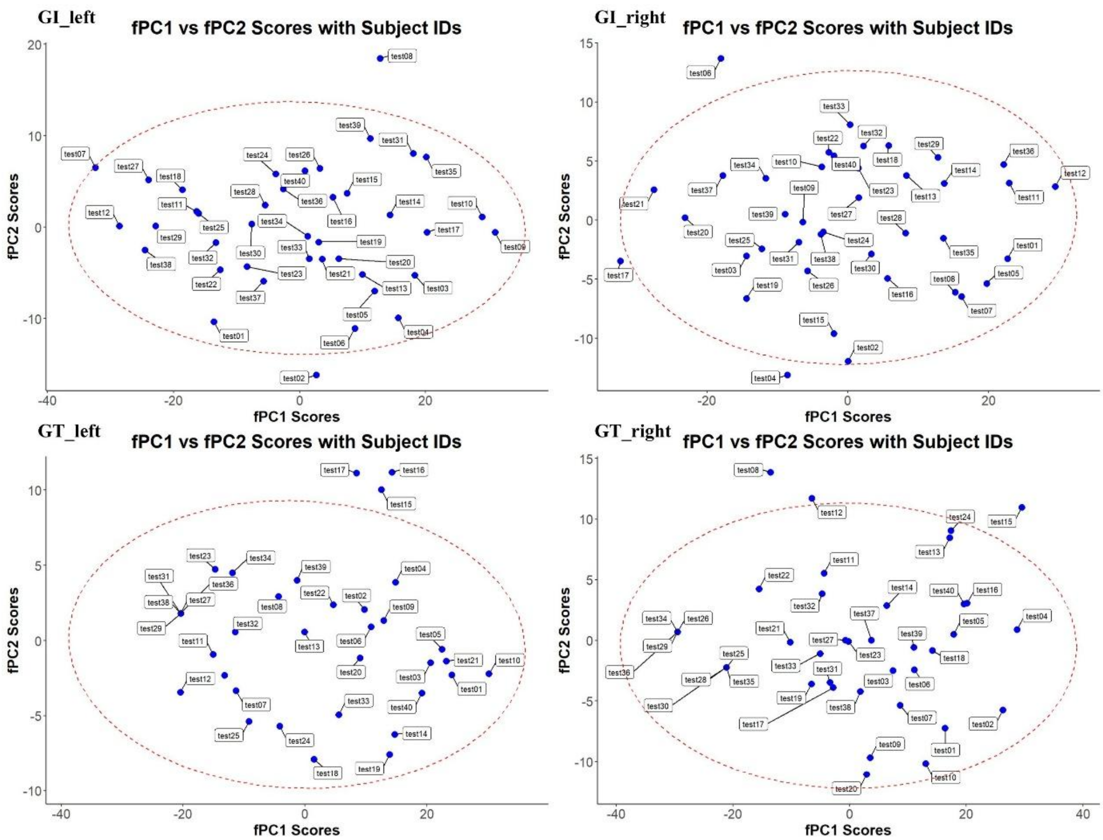


**Figure 1A**. Illustration of fPC1-fPC2 plot in GI and GT of dominant and non-dominant foot with confidence ellipses (95%) in the dash circle.

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