Analysis of Foot Placement in Gait with Constant Lateral Disturbance

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Abstract— **The study of gait stability has sought to understand the fundamental mechanisms that lead us to recover from a disturbance, whether constant or not. Correct foot placement has been identified as one of the main strategies used to maintain and recover balance during gait. In this study, we evaluated the foot placement estimator (FPE) as a measure of stability when applying a constant disturbance to the gait of young people on a treadmill. The results showed that individuals decreased stride width in response to disturbance and this reflected in greater instability in foot positioning, especially in the contralateral foot. This study demonstrated the usefulness of the stability measure derived from the FPE in gait stability studies, especially in disturbed gait.**

Keywords— **gait stability, foot placement estimator, external perturbation, balance.**

I. INTRODUCTION

The study of gait stability has been of interest to many researchers, especially to understand the fundamental mechanisms that lead to an increased risk of falling [1]–[3]. The disturbance during gait is commonly used as a method to assess the ability to recover balance and investigate the strategies adopted by the walker as a form of balance control [4], [5].

The balance control during gait is a complex process regulated by strategies that seek to lead to a stable trajectory of the body's center of mass (CoM) [6], [7]. Correct foot placement has been identified as one of the main strategies used to maintain and recover balance during gait [8], [9], as the location of the foot determines the origin and possible directions of the ground reaction force, determined by the center of pressure (CoP) which is taken as the controller of the CoM displacement [10].

The importance of foot positioning for stability during gait is reflected in numerous studies that seek to understand the mechanisms and fundamental aspects that lead us to step where we step [8], [11]–[13].

Some studies sought to theoretically estimate the optimal place where we should position the foot in order to maintain or restore balance during gait. Among some methods is the foot placement estimator (FPE), a method based on a simplified inverted pendulum model that analyzes the conservation of energy during the heel strike to determine the optimal positioning of the foot in order to lead to balance in just one step [14]–[16].

As a stability measure, the FPE has not yet been widely explored [17], [18], especially to assess its robustness in disturbed gears. The present study seeks to expand the stability study by evaluating the foot placement of a participant walking on a motorized treadmill with a constant mediolateral perturbation (ML). The FPE was used to estimate how stable the participants' foot placement was during the disturbance compared to the undisturbed situation.

II. MATERIAL AND METHODS

A. Subjects

A total of 6 young adults (Table I) participated in this study. The inclusion criteria were as follows: to be in good health, to have the ability to walk independently without an assistive device, to be without neurological impairments, to be without a history of musculoskeletal surgery and to be without any injury or pain at the time of data collection.

TABLE I. CHARACTERISTICS OF THE PARTICIPANTS.

ID	Gender	Dominant Leg	Years	Weight (kg)	Height (m)
1	M	R	25.9	85.35	1.84
2	M	R	31.0	84.70	1.74
3	M	L	28.4	68.60	1.79
4	F	L	22.4	67.45	1.53
5	F	R	24.7	64.00	1.66
6	F	R	30.1	57.30	1.64
Total			**27.1±2.8**	**71.23±9.19**	**1.70±0.09**

The participants voluntarily signed an informed consent form. Next, they participated in testing protocols previously approved by the Local Research Ethics Committee.

B. Equipment

A total of 41 markers were placed on all participants (head, trunk, upperarm and forearm, hand, thigh and shank, and foot - including 2nd and 5th metatarsus) based on the total body PlugInGait markers configuration (Vicon, Oxford Metrics, Oxford, UK).

The markers were used for gait assessment, and a kinematic analysis was performed using a 3D motion capture system consisting of 12 infrared cameras and a sampling rate of 120 samples/s.

C. Protocol

Participants became familiar with the treadmill during two minutes of walking, while the preferred walking speed (PWS) was determined according to a reported protocol [19].

After this period, the participants performed three walks of 2 minute each in the PWS, an undisturbed trial (UDT), one perturbed trial with a weight (5% of body mass) attached to the waist and pulling in the mediolateral direction (ML) to the dominant side (DMT) and another trial with perturbance to the nondominant side (NDT), in random order, with a 1 minute of rest between them.

During daily activities, several perturbations are applied to the gait, such as carrying a backpack unilaterally, bags in only one hand, or even pushing by other people. To simulate the correct magnitude of these perturbations, previous tests were performed with perturbations of 2%, 5%, 7% and 10% of body weight. Participants were found to be unable to walk satisfactorily at 7% and 10% body weight, while others did not feel challenged when pulled by 2% of body weight. Therefore, the disturbance of 5% of body weight was established.

It is known that the ML direction is more challenging for gait stability as it has a smaller base of support than the anteroposterior (AP) one [20]. Therefore, in this study only ML perturbations were performed.

The disturbance equipment allowed free movement of the arms during the lateral perturbation, as shown in Fig. 1.

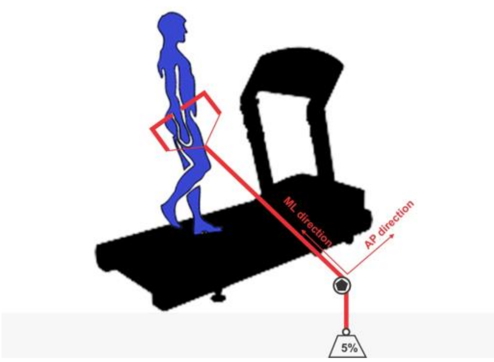

Fig. 1 – Mediolateral perturbation protocol

D. Calculations

D.1. Pre-processing data

Before data analysis was performed, the data were filtered using a low-pass, zero-lag, fourth order Butterworth filter with a cut-off frequency of 6Hz. The kinematic data were analyzed with a custom MatLab code (R2020a, MathWorks, Natick, MA).

D.2. Gait parameters

The heel strike and toe-off gait events were obtained by anteroposterior (AP) positioning relative to the pelvic center of mass and the heel and 2nd metatarsal markers, respectively, according to [21].

Walking speed was obtained by heel marker speed during stance phase [22]. In addition, we calculated the single stance and double stance times for each leg, expressed as a percentage of the gait cycle, to verify possible compensations in the movement of the disturbed leg. Step width and length were calculated as the distance between the heel marker at the initial contact of two subsequent steps, in the ML and AP direction, respectively.

D.3. Foot placement estimator

The Foot Placement Estimator (FPE) is a predictive model developed by Wight et al. [14], [16] which seeks to establish the correct point for placing the foot to restore balance in a single step (if necessary) during gait. The FPE is based on a simplified pendulum model consisting of a single body with 3 degrees of freedom (planar translation and rotation) and two massless contact points representing the feet.

The FPE calculation is based on the location where the biped should place its point of contact so that, after impact on the ground, it has enough kinetic energy to progress the movement to the upright position.

The FPE equations assume movement in a vertical plane (2D). But to represent 3D movement this vertical plane is guided by an instantaneously plane of progression. The first axis of the plane of progression is the (global) vertical axis, and the second axis is perpendicular to the vertical axis and to the vector formed by the horizontal component of the participant's angular momentum about the ground projection of the center of mass (CoM) [16], [17].

The total body angular velocity ($\dot{\theta}$) is calculated as:

$$\dot{\theta} = \frac{H_{tot}}{J_{CoM}} \tag{1}$$

In which H_{tot} é the total body angular momentum about the CoM and J_{com} is the total body inertia component perpendicular to the plane of progression, calculated by parallel axes theorem from segments inertia.

The leg angle (ϕ) that allows the inverted pendulum model to stop in static equilibrium in a single step is calculated by solving the following equation:

$$\frac{\left[mh(v_x cos\phi + v_y sen\phi)cos\phi + J_{CoM}\dot{\theta}cos^2\phi\right]^2}{mh^2 + J_{CoM}cos^2\phi} + 2mghcos\phi(cos\phi - 1) = 0 \tag{2}$$

Where m is the participant's mass, h is the vertical height of the CoM, v_x and v_y are the horizontal and vertical velocities of the CoM in the plane of progression, and g is the acceleration of gravity.

The location of the FPE is obtained by projecting the angle ϕ between the vertical line of the CoM to the ground and the line of the CoM to the contact point (foot) of the model, as shown in Fig. 2.

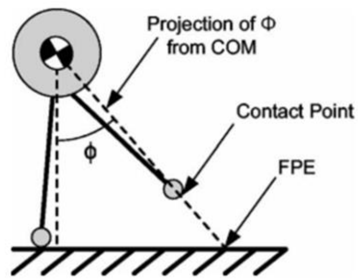

FIG. 2 – FPE LOCATION BY A PROJECTION OF ϕ FROM CENTER OF MASS

Mathematically the FPE is calculated as:

$$X(\phi) = h \cdot tan(\phi) \quad (3)$$

The value of $X(\phi)$ is then rotated in the plane of progression to obtain the 3D components, $X_{ML}(\phi)$ and $X_{AP}(\phi)$. The stability measure based on the FPE is then calculated as: in the ML direction as the difference between the 5th metatarsus marker and $X_{ML}(\phi)$ called $DFPE_{ML}$; in the AP direction as the difference between the 2nd metatarsus marker and $X_{AP}(\phi)$ called $DFPE_{AP}$. These measurements are calculated at heel strike instants.

Positive values of $DFPE_{ML}$ and $DFPE_{AP}$ indicate that the foot has covered the FPE and the participant can stop in balance on the next step, in this way, the measurements can indicate how stable the walker's gait pattern is.

D.3. FPE procedures

The variables for calculating the FPE were obtained as follows:

- The body and segments CoM were extracted from the Vicon software using a FullBody Plugin Gait model.
- The inertia of the segments was calculated by the scaling method using 27 anthropometric measurements [23] in the KwonBSP software [24].
- The angular velocity of the segments was obtained using the Vicon ProCalc software.

E. Statistical Analysis

The repeated measures analysis of variance (ANOVA) with mixed design was used to compare the conditions followed by a post-hoc test with Bonferroni correction in the cases where the main effect was significant. Statistical analysis was performed using SPSS software, version 23 (SPSS Inc., Chicago, IL, USA), with a significance level set at α <0.05.

III. RESULTS

Table II shows the temporal variables of gait in undisturbed (UDT) and disturbed (DMT and NDT) conditions.

TABLE II. TEMPORAL VARIABLES FOR UNDISTURBED AND DISTURBED TRIALS.

Temporal variables	**Conditions**			**p**
	UDT	**DMT**	**NDT**	
Stride time (s)	1.106±0.059	1.097±0.066	1.092±0.069	0.331
Double Support (%)	31.128±1.914	31.238±1.959	31.220±1.948	0.610
Single Support (%)	65.564±0.955	65.599±0.978	65.633±0.976	0.510
Single Dominant Support (%)	65.652±1.075	65.712±1.122	65.624±1.032	0.587
Single Nondominant Support (%)	65.475±0.912	65.486±0.861	65.642±0.962	0.406
Swing Phase (%)	34.437±0.958	34.406±0.975	34.370±0.977	0.531
Dominant Swing Phase (%)	34.348±1.077	34.293±1.119	34.380±1.035	0.603
Nondominant Swing Phase (%)	34.525±0.913	34.517±0.858	34.361±0.962	0.409

Analysis of Repeated Measures (ANOVA).

The statistical analysis of the spatiotemporal variables showed that there was a difference in the step width (p = 0.026. F = 5.348) between the conditions, as shown in Fig. 2. There was a decrease in step width in the NDT condition (Bonferroni post hoc test, p=0.045) and a decreasing trend in the DMT condition (Bonferroni post hoc test, p=0.065) compared to the undisturbed UDT condition. There was no statistical difference in step length between the conditions.

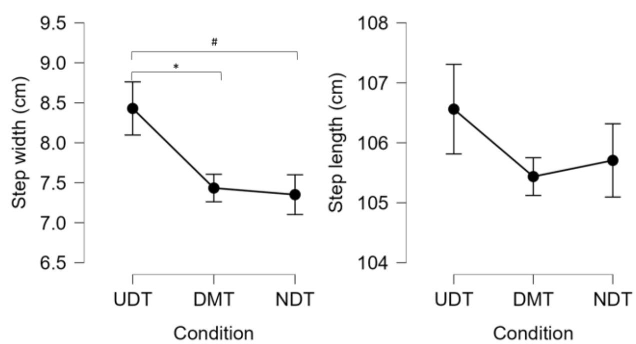

FIG. 1 – SPATIOTEMPORAL VARIABLES IN UNDISTURBED AND DISTURBED CONDITIONS. BONFERRONI POST HOC TEST: * P = 0.065 AND # P = 0.045.

The average stability measures in the ML and AP directions can be seen in Fig. 3. Statistical difference was found between the conditions only for $DFPE_{ML}$ (p=0.019, F=6.053), the values indicated that the disturbed condition NDT was more unstable than the undisturbed condition UDT (Bonferroni post hoc test, p=0.022).

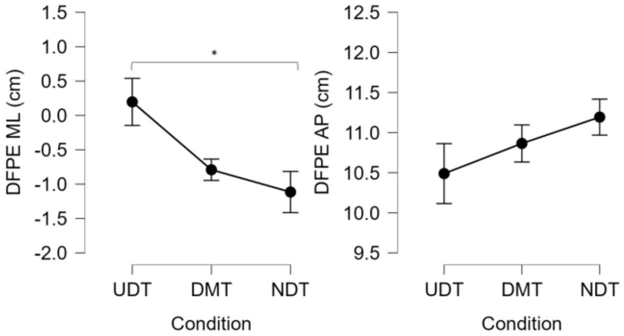

FIG. 2 – AVERAGE STABILITY MEASURES IN UNDISTURBED AND DISTURBED CONDITIONS. BONFERRONI POST HOC TEST: * P = 0.019.

The results of stability measurements ($DFPE_{ML}$ and $DFPE_{AP}$) separated by dominant and non-dominant leg can be seen in Table III and Fig. 4. Analyzing Table III and Fig., 4 it was verified that there was a significant difference in the stability measure between the conditions in both legs in the ML direction, however, the post hoc analysis showed that this difference indicated different sources of instability according to the perturbation condition was applied.

TABLE III. STABILITY MEASURES SEPARATED BY DOMINANT AND NON-DOMINANT LEG.

		Conditions			p
		UDT	DMT	NDT	
DFPE ML	***Dom. Leg***	0.024±5.541[a]	0.261±6.408[b]	-3.236±7.296[a,b]	**0.001**
	N-dom. Leg	0.413±6.580[c]	-1.836±6.519[c,d]	1.057±7.485[d]	**0.001**
DFPE AP	***Dom. Leg***	11.410±4.244	10.718±5.311[e]	12.728±5.143[e]	**0.014**
	N-dom. Leg	9.437±6.961	10.988±6.896	9.547±7.584	0.107

Analysis of Repeated Measures (ANOVA). Bonferroni post hoc test: a = 0.001, b<0.001, c=0.045, d= 0.005 and e = 0.014. Bolded p-values means statistically significant difference between conditions.

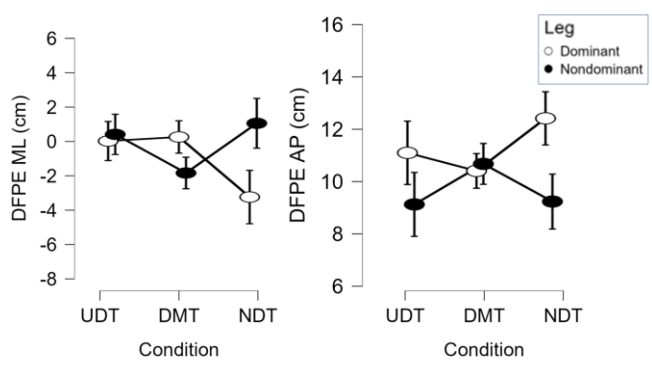

FIG. 3 – STABILITY MEASURES IN ML AND AP DIRECTION SEPARATED BY DOMINANT AND NON-DOMINANT LEG.

The dominant leg walked more unstable ($DFPE_{ML}$ more negative) when the perturbation was applied to the non-dominant side (NDT), whereas the non-dominant leg was more unstable when the perturbation was applied to the participant's dominant side (DMT).

In the AP direction, there was a significant difference only for the dominant leg and indicated that this leg sought greater stability ($DFPE_{AP}$ more positive) when contralaterally disturbed.

IV. DISCUSSION

In this study, we evaluated gait stability in disturbed and undisturbed conditions in the ML direction. Foot placement was used as a measure of stability, in addition to temporal and spatiotemporal measures of gait.

No differences were found in the temporal variables of stride time, double support, single support (average, dominant and non-dominant leg), swing phase (average, dominant and non-dominant leg) between the gait conditions with disturbance (DMT and NDT) and without disturbance (UDT), Table II. This result may indicate that the participants did not modify the velocity of the ipsilateral leg as compensation for resistance to lateral weight.

Similar to gait with external lateral stabilization [25] and higher velocities [26], there was a significant reduction in step width in disturbed conditions compared to the normal condition (Fig. 2). It is assumed that one way to maintain stability in a lateral disturbance is to contralaterally compensate for the force exerted by the weight, which results in a decrease in the base of support and, consequently, a smaller step width. Despite not calculating the CoP in this study, some participants reported greater pressure on the outer edges of the ipsilateral feet during the disturbance, which may corroborate our assumption.

The decrease in step width resulted in a more unstable positioning of the feet in the mediolateral direction ($DFPE_{ML}$) under disturbed conditions (Fig. 3). Just as there was no change in step length (Fig. 2), gait stability based on AP foot positioning was not altered by disturbing gait.

The stability assessment using the FPE also showed that the foot contralateral to the disturbance (dominant leg in NDT condition and non-dominant leg in DMT condition) was positioned medially ($DFPE_{ML}$ more negative) to the stable positioning established by the FPE in the ML direction (Table II and Fig. 4). This may indicate that to make gait more stable in these disturbed conditions, a greater moment attributed by the pelvis to the swing leg would be necessary.

Although there was no significant difference in step length and average DFPEAP, the analysis by leg showed that in the AP direction the dominant leg of the participants sought a more stable positioning when the perturbation was applied contralaterally, which may indicate an attempt to compensate for the dominant leg to position the foot in a more stable region.

These results indicate the robustness of the FPE in pointing out patterns of change in the correct positioning of the foot in conditions of lateral disturbance and thus expand the use of this measure as a way of assessing gait stability.

V. CONCLUSION

In this study, constant lateral perturbations were applied during the gait of young people on a treadmill. Temporal and spatiotemporal variables were evaluated, in addition to the stability measure based on the FPE method of foot positioning. Such parameters were compared with undisturbed gait.

The results showed that there was no compensation in the temporal variables of the disturbed gait. But there was a decrease in step width in the disturbed conditions and this reflected in higher average instability in the ML direction. Greater instability was also found in the positioning of the feet contralateral to the application of the disturbance.

This study demonstrates the potential use of the FPE foot positioning method as a measure of stability in disturbed gait. With these results, it will be possible to expand the understanding of the fundamental mechanisms that lead to a greater risk of falling during gait.

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