The required coefficient of friction in Parkinson's disease: people with freezing of gait

Ana Francisca Rozin Kleiner, PhD[a,b]
Diana M. Cubillos, MS[c]
Camila Pinto, PT[c]
Ana Paula Salazar, MS[c]
Ritchele R. Marchese, MS[c]
Ricardo M. L. Barros, PhD[d]
Manuela Galli, PhD[b]
Aline S. Pagnussat, PhD[e]

[a] University Center of Anápolis - Uni Evangélica, Anápolis, Goiás, Brazil
[b] Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milan, Italy
[c] Movement Analysis and Neurological Rehabilitation Laboratory, Universidade Federal de Ciências da Saúde de Porto Alegre (UFCSPA), Porto Alegre, RS, Brazil
[d] Laboratory of Instrumentation for Biomechanics, Faculty of Physical Education, University of Campinas, Campinas, Brazil
[e]Graduate Program in Rehabilitation Sciences, Universidade Federal de Ciências da Saúde de Porto Alegre (UFCSPA), Porto Alegre, RS, Brazil

The two first authors had «Equal contribution and Credit».

Correspondence to: Ana Francisca Rozin Kleiner
E-mail: anafrkleiner@gmail.com

Summary

The required coefficient of friction (RCOF) is frequently reported in the literature as an indicator of slip propensity, a consequence of the collisional aspect of legged locomotion. Little is known about the RCOF in pathological gait. Therefore, this study aimed to quantify the RCOF in subjects with Parkinson's disease (PD) and freezing of gait (FOG) during the OFF-pharma phase, and to investigate the interplay between RCOF parameters and ankle kinematic and kinetic gait variables. Fourteen subjects with PD and 14 healthy age-matched subjects were instructed to walk barefoot at self-selected speed over a force platform. The RCOF curve was obtained as the ratio between the tangential and vertical ground reaction forces. Then, the following discrete variables were identified: P1COF (the peak at the loading response phase), V1COF (the valley at mid-stance phase) and P2COF (the peak at push-off phase). Stepwise multiple regressions were applied to observe the influence of the gait speed and ankle kinematic and kinetic gait variables on RCOF variables. In subjects with PD and FOG the gait speed is a predictor of the RCOF in the loading response phase; plantarflexion and the plantarflexion moment are strong predictors of the RCOF in mid-stance; finally, push-off power is a predictor of RCOF increasing in the push-off phase. These results characterized the biomechanical strategies adopted by subjects with PD and FOG during gait in order to avoid falls.

KEY WORDS: freezing of gait, gait analysis, kinematics, kinetics, Parkinson's disease, required coefficient of friction.

Introduction

Freezing of gait (FOG) is a transient phenomenon whereby subjects with Parkinson's disease (PD) suddenly become unable to start or continue gait (Giladi and Nieuwboer, 2008). Subjects with PD and FOG show gait variability, a feature related to the risk of falling and its consequences (Nakamura et al., 1996; Hausdorff et al., 1997; Maki, 1997; Hausdorff et al., 1998; Bloem et al., 2001; Hausdorff et al., 2001a; Hausdorff et al., 2001b; Wieliñski et al., 2005; Hollman et al., 2007; Kleiner et al., 2018a). As the biomechanics of gait are completely altered in individuals with PD and FOG, how can these individuals interact with a supporting surface without slipping? The required coefficient of friction (RCOF) is frequently reported in the literature as an indicator of slip propensity (Beschorner et al., 2016), a consequence of the collisional aspect of legged locomotion. A slip occurs when the amount of friction at foot/floor interfaces necessary to prevent slipping (RCOF) is greater than the available friction. The RCOF depends on features of the individual and his/her gait biomechanics, while the available friction depends on environmental features, such as the tribology of shoe/foot soles and supporting surface characteristics. The more slippery a floor surface is (i.e. from dry to soapy), the greater the risk of slipping and falling if gait biomechanics are not adjusted (Redfern et al., 2001; Chang et al., 2011).
Categorically, whenever the foot forces normally generated during gait (RCOF) are not biomechanically adjusted to counteract shear forces and prevent slipping, slipping will be imminent. So, the likelihood of slipping increases either when the RCOF increases, or when the available friction decreases.
The RCOF is calculated as the ratio of tangential to vertical ground reaction forces during the stance phase (Redfern et al., 2001; Chang et al., 2011); the RCOF curve is characterized by two peaks and one valley (Fig. 1). The peaks represent, respectively, the highest shear forces occurring in the loading response and terminal stance phases, whereas the valley is observed in the mid-stance phase. The lower the value of the valley, the greater the range of motion (ROM) of the lower limb joints (Kleiner et al., 2014; Kleiner et al., 2015a; Kleiner

et al., 2015b; Pacifici et al., 2016; Kleiner et al., 2017; Kleiner et al., 2018b).

The RCOF has previously been quantified both in subjects with PD and in subjects affected by other diseases, such as stroke, multiple sclerosis and cerebral palsy (Kleiner et al., 2014; Kleiner et al., 2015a; Kleiner et al., 2015b; Pacifici et al., 2016; Kleiner et al., 2017; Kleiner et al., 2018b). Recently, Kleiner et al. (2017) characterized the RCOF curve in subjects with PD in the ON-pharma phase.

They observed that subjects with PD had lower RCOF values during the loading response and terminal stance phases and higher RCOF values during the mid-stance phase when compared with the healthy aged-matched control group. Still, a very high correlation (90.3%) was observed between RCOF in loading response and the Timed Up and Go Test (TUG) (Podsiadlo and Richardson, 1991), with higher RCOF values found to be associated with increased time required to carry out the TUG. Taking a long time to accomplish the TUG means an increased risk of falling in subjects with PD (Mak and Pang, 2009). Thus, these results indicate that the friction that occurs during the loading response phase may be a critical factor for falls in PD gait. However, in the aforementioned study, only subjects without FOG and in the ON-pharma phase were evaluated. A patient with PD and FOG in the OFF-pharma phase is more susceptible to falling (Bloem et al., 2001; Mak and Pang, 2009; Kerr et al., 2010; Allen et al., 2013).

In view of these observations, the present study set out to calculate RCOF values in subjects with PD and FOG during the OFF-pharma phase and to investigate the interplay among RCOF parameters and ankle kinematic and kinetic gait variables. A complete description of the correlations between the various RCOF and ankle kinematic and kinetic (moment and power) parameters could provide new insights into balance control during the gait support phase in these subjects.

Materials and methods

The Ethics Committee of Universidade Federal de Ciências da Saúde de Porto Alegre (protocol 1.333.131) approved this cross-sectional study, which also complies with the STROBE statement. Written informed consent was obtained from all the participants before the start of every procedure. The study was carried out from December 2015 to September 2016.

Participants

Fourteen subjects with PD and FOG (PD group) and 14 healthy aged-matched control group subjects (HC group) took part in this study. They were recruited using the convenience sampling method (advertising for participants through hospitals, associations and other entities in the city of Porto Alegre, state of Rio Grande do Sul, Brazil).

The sample size was calculated to detect a difference of 0.11 in the second maximum value in the RCOF curve (push-off - P2COF), assuming a standard deviation of 0.1, a power of 80% and a two-sided significance level of 5% (Kleiner et al., 2015a). Given an anticipated dropout rate of 10%, we included 14 participants in each group.

The inclusion criteria for the participants with PD were: male and female subjects with a diagnosis of idiopathic PD according to the London Brain Bank Criteria; age between 50 and 80 years; moderate to high risk of falls score on the TUG (Mak and Pang, 2009); presence of regular daily FOG episodes quantified by the Freezing of Gait Scale (FOG Scale - minimum score of 12) (Giladi et al., 2009); a minimum score of 20 or 24 on the Mini-Mental State Examination (MMSE) for individuals without or with a formal education, respectively (Almeida, 1998). The exclusion criteria were: any secondary musculoskeletal disorder involving the lower limbs, such as chondral injuries, ligament injuries and ankle sprains which, causing pain or impaired motion, could impede the gait evaluation; and patients previously submitted to deep brain stimulation. The study also included a reference group of healthy subjects (HC group), paired by age and sex with the PD patients. The members of the HC group were healthy adults, male or female, aged between 50 and 85 years. Exclusion criteria: previous history of neurological or musculoskeletal disorders that induced visible gait abnormalities.

The clinical evaluation of the patients with PD was carried out before the beginning of the procedures and included: MMSE, Freezing of Gait Questionnaire (FOG-Q), Motor Section (III) of the Unified Parkinson's Disease Rating Scale (UPDRS III) (Goetz et al., 2008) (OFF-levodopa phase), Hoehn & Yahr Scale (H&Y, Goetz et al., 2004) (OFF-levodopa phase) and the TUG (OFF-levodopa phase) (Podsiadlo and Richardson, 1991). Moreover, during data acquisition, all participants were in the OFF-pharma phase.

Experimental protocol

Data collection was performed at the Movement Analysis and Neurological Rehabilitation Laboratory at Universidade Federal de Ciências da Saúde de Porto Alegre (UFCSPA) - Brazil, using an optoelectronic system involving six Smart-D cameras (BTS Bioengineering, Italy) with a sampling rate of 100 Hz, two tri-axial force platforms (BTS Bioengineering, Italy, P6000 model) with a sampling rate of 500 Hz and two TV camera Video Systems (BTS, Italy) synchronized with the force platform and the optoeletronic system. For data acquisition, 22 spherical retro-reflective passive markers (14 mm diameter) were placed on the skin surface on the lower limbs and trunk of the participants at specific landmarks according to the protocol described by Davis et al. (1991).

Participants were asked to walk barefoot at a self-selected speed —their normal walking speed — at least six times along an 8-meter pathway. They were allowed to take a rest break after each trial. As the RCOF is affected by the friction between the foot/shoe and floor, to avoid shoe type influencing performance, the participants were asked to undertake each test barefoot (Kleiner et al., 2015b).

Raw data were processed using dedicated software (SMARTanalyzer, Version 1.10.458.0 by BTS Bioengineering, Italy) to calculate the following variables: 3D ground reaction force, GRF [N]; ankle dorsi-plantarflexion moment [N*m/kg]; and ankle joint power [W/kg].

To compute the RCOF the first step was to calculate the tangential force (FT). This was computed as the resulting sum of FX (lateral GRF) and FY (anterior-posterior GRF) as shown in Equation 1:

$$FT = \sqrt{(FX^2+FY^2} \qquad (1)$$

Then, the RCOF curve was calculated as the ratio of the FT by the vertical ground reaction force (FZ) during standing – Equation (2):

$$RCOF = \frac{FT}{FZ} \quad (2)$$

Once the RCOF had been computed, the following discrete variables were identified as shown in Fig. 1:
P1COF: the local maximum of the RCOF curve occurring at about 10 to 20% in the loading response phase (Chang et al., 2011);
V1COF: another local maximum occurs at ~90% in the push-off phase (Chang et al., 2011);
P2COF: the minimum value of RCOF during the mid-stance phase (Kleiner et al., 2015b; Kleiner et al.,2017; Kleiner et al., 2018b).
Then, the RCOF variables (P1COF, V1COF, P2COF) were correlated with the following kinematic and kinetic parameters:

- gait speed [m/s]: average value of the speed of progression
- plantarflexion [°]: this represents the minimum value (negative value) of the ankle angle in stance. It occurs during loading response phase (Figure 2a)
- dorsiflexion [°]: this represents the maximum value (positive value) of the ankle angle in stance. It occurs during terminal phase (Figure 2a)
- ankle ROM [°]: ROM, in the gait cycle, of the ankle joint in sagittal plane, computed as the difference between the maximum and minimum values of the plot (Fig. 2a)
- plantarflexor moment (MOM) [N*m/kg]: this is the maximum ankle plantarflexion moment (i.e. the peak in the ankle dorsi-plantarflexion moment curve) (Fig. 2b)
- absorption power (absorption PWR) [W/kg]: this is the minimum peak of the ankle joint power curve. It occurs in the pre-swing phase of the cycle gait (Fig. 2c)
- push-off power (push-off PWR) [W/kg]: this is the maximum ankle joint power (i.e. the peak in the ankle joint power curve) (Fig. 2c).

For each patient, a representative datum was considered and used in the correlation analysis. The GRF values were normalized by body weight. Moreover, since the variables RCOF, MOMmax, and PWRmax are known to depend on gait speed (Winter, 1983; Kim et al., 2005), they were normalized by this parameter. The previously described parameters were computed for each trial, and the average values were calculated considering all six trials.

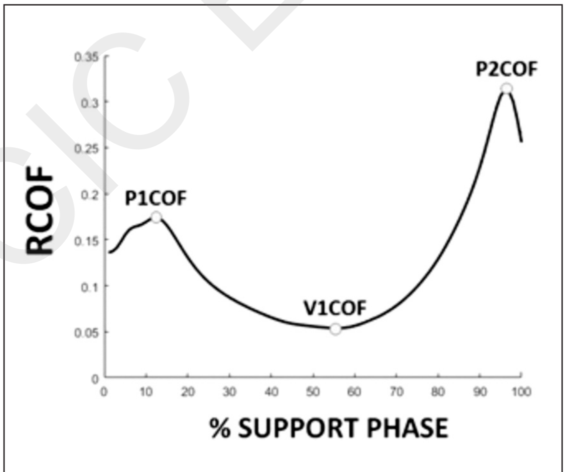

Figure 1 - Required coefficient of friction (RCOF) variables.

Statistical analysis

In order to characterize the parameter RCOF in PD gait, the following analyses were carried out. The RCOF, ankle kinematic and kinetic values were compared between the PD group and the HC group, by means of the Student t test for parametric data and the Mann-Whitney test for non-parametric data. Results for the parametric data are presented as average values and standard deviation, and for the non-parametric data as median values and interquartile range.

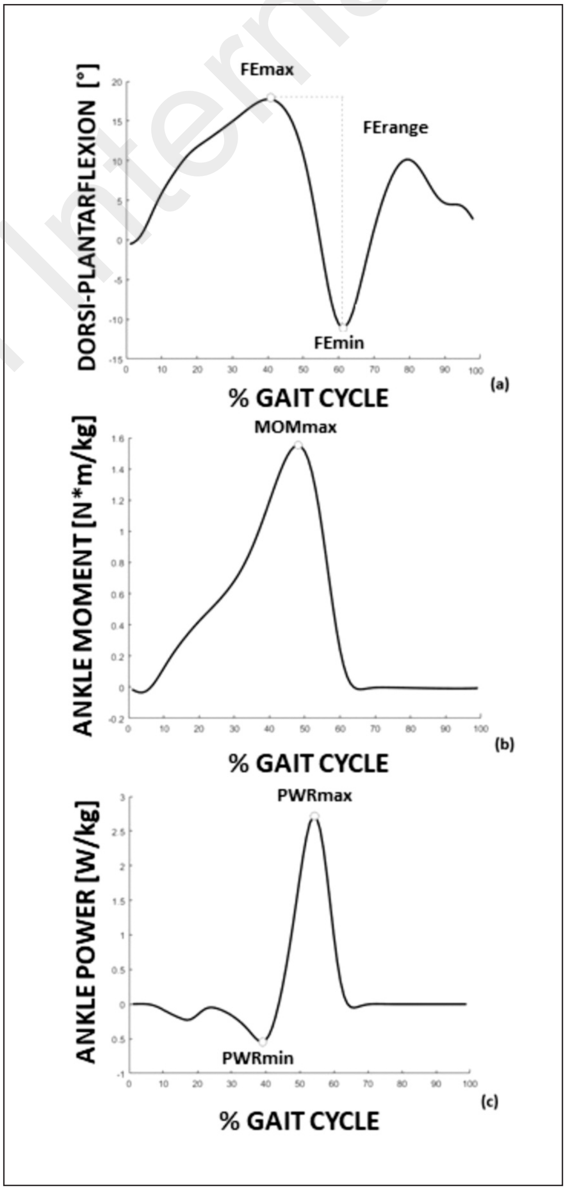

Figure 2 - Ankle kinematic and kinetic parameters.

Spearman's correlation test was used to assess the correlations between the RCOF variables and the kinematic and kinetic parameters. The degrees of correlation can be understood as follows (Taylor, 1999): 0.9 to 1 indicates a very high correlation; 0.7 to 0.9 indicates a high correlation; 0.5 to 0.7 indicates a moderate correlation; 0.3 to 0.5 indicates a low correlation, and 0 to 0.3 indicates little to no correlation. All tests were two-tailed. Finally, the stepwise multiple regression was used with P1COF, V1COF, and P2COF as dependent variables and the ankle kinematic and kinetic parameters as independent variables to identify factors that influence RCOF in PD gait.

IBM SPSS Statistics v.22 software (IBM, Armonk, NY, USA) was used for statistical analysis with the level of significance set at $\alpha < 0.05$.

Results

The demographic characteristics of the two groups are shown in Table I. No differences in anthropometric features were found between the PD and HC groups (Table I). The comparisons between the PD and HC groups for each dependent variable are presented in Table II. Differences between groups were found in P1COF, V1COF, plantarflexion and gait speed. The PD group showed higher P1COF and V1COF values, and lower plantarflexion and gait speed values compared with the HC group.

The Spearman correlations (R_S) are shown in Table III. P1COF showed a moderate negative correlation with gait speed (r = .592; Table III). On the other hand, V1COF presented a moderate positive correlation with plantarflexion (r = .60), a moderate negative correlation with ankle ROM (r = .527) and gait speed (r = .579), and a low correlation with plantarflexion MOM (r= .444) and absorption power (r = .435). Finally, P2COF showed a moderate positive correlation with push-off PWR (r = .549).

Multiple linear regressions were performed to predict the RCOF variables based on kinematic and kinetic ankle parameters. For the P1COF, a significant regression equation was found for gait speed ($F_{1,24}$ = 11.982; p = 0.002), with an R^2 of 0.333. For the V1COF, a significant regression equation was found for plantarflexion and plantarflexion MOM ($F_{1,24}$ = 16.735; p=0.001), with an R^2 of 0.593. Finally, for P2COF a significant regression equation was found for push-off PWR ($F_{1,24}$ = 11.179; p=0.003), with an R^2 of 0.318.

Discussion

Our results indicated that the PD group had higher RCOF values in the loading response (P1COF) and mid-stance (V1COF) phases, as well as lower plantarflexion and gait speed when compared with the HC group. In healthy subjects, a higher P1COF allows the deceleration phase for loading acceptance, and the V1COF is the valley observed in the mid-stance phase

Table I - Demographics and clinical characteristics of the participants.

Characteristic	PD group (n=14)	HC group (n=14)	p
Age (years)	65.85±8.49	61.86±5.11	.117
Body weight (kg)	84.12±21.90	72.33±10.02	.352
Height (cm)	167.31±0.095	166.64±0.10	.862
FOG-Q	14.31±2.56	-	-
UPDRS	23.77±4.98	-	-
H&Y	2.42±0.53	-	-
TUG (s)	17.84±3.54	10.32±1.17	.001*

Abbreviations: PD=Parkinson's disease; HC=healthy control; FOG-Q= Freezing of Gait Questionnaire score; UPDRS=Unified Parkinson's disease Rating Scale score; H&Y= Hoehn & Yahr Scale score; TUG= Timed Up and Go Test. All values are mean and standard deviation.

Table II - Comparison between groups.

Variable	PD Group	HC Group	p
P1COF	0.278 (0.223 / 0.332)	0.197 (0.169 / 0.224)	.001*
V1COF	0.044 (0.035 / 0.052)	0.033 (0.026 / -0.040)	.023*
P2COF	0.321 (0.274 / 0.368)	0.315 (0.276 / 0.353)	.770
Dorsiflexion [°]	20.223 (16.353 / 24.092)	19.742 (18.135 / 21.352	.544
Plantarflexion [°]	-6.907 (-10.193 / -3.622)	-12.380 (-16.914 / -7.846)	.027*
Ankle ROM [°]	27.546 (22.648 / 32.443)	32.126 (27.788 / 36.465)	.142
Plantarflexor MOM [N*m/kg]	1.482 (1.234 / 1.730)	1.357 (1.208 / 1.507)	.430
Absorption PWR [W/kg]	-1.005 (-1.207 / -0.802)	-0.905 (-1.131 / -0.680)	.223
Push-off PWR [W/kg]	2.394 (1.950 / 2.838)	2.772 (2.323 / 3.219)	.239
Speed [m/s]	0.990 (0.839 / 1.141)	1.177 (1.072 / 1.283)	.013*

Abbreviations: PD=Parkinson's disease; HC=healthy control; ROM=range of motion; MOM=moment; PWR=power

Table III - Results of Spearman's correlation analysis between RCOF and kinetic/kinetic gait parameters.

Variable		DF [°]	PF [°]	Ankle ROM [°]	Plantarflexion MOM [N*m/kg]	AbsPWR [W/kg]	Poff PWR [W/kg]	Gait speed [m/s]
P1COF	R_S	- .159	.271	-.327	.440	-.277	.019	-.592
	p	.420	.153	.089	.022*	.171	.925	< .001
V1COF	R_S	.195	.600	-.527	.444	-.435	-.012	-.579
	P	.320	.001*	.004*	.02*	.027*	.954	< .001
P2COF	R_S	.359	-.053	.152	.196	-.320	.549	-.030
	P	.061	.787	.440	.327	.111	.003*	.881

Abbreviations: RCOF=required coefficient of friction; DF = dorsiflexion; PF = plantarflexion; ROM = range of motion; MOM=moment; AbsPWR = absorption power; Poff PWR = push-off power; RS = Spearman correlation test values; p=significant difference.

when the deceleration phase starts. At V1COF the RCOF values decrease due to gait progression. This happens in order to reverse the movement deceleration and initiate the acceleration phase (Kleiner et al., 2015b), allowing the necessary grip and, consequently, the transmission of the developed forces to the kinematic chain, giving continuity to the gait cycle (Kleiner et al., 2015a).

The higher P1COF and V1COF values found in the PD group might be related to festinating gait, the typical gait pattern of PD freezers. Festinating gait is characterized by small, rapid steps, taken in an attempt to keep the center of gravity (COG) positioned between the two feet as the trunk leans forward involuntarily, shifting the COG forward. In an attempt to correct balance, instead of taking one or two large corrective steps, these patients take hypsometric steps, bringing their COG over the front part of their feet. In order to compensate hypokinesia and in an attempt to avoid falling, their first strategy is to increase P1COF according to gait speed, to guarantee the deceleration phase for loading acceptance.

Moreover, the higher V1COF is explained by the reduced plantarflexion angle and the increased plantarflexion MOM. This strategy allows gait progression. Plantarflexor muscles are an important muscle group in gait speed regulation in healthy subjects, as they generate a large part of the energy required to move limbs forward during the push-off phase (Neptune et al., 2001; Anderson and Pandy, 2003; Neptune et al., 2008). This phase is characterized, at the ankle, by a shortening of the plantarflexor muscles or a concentric contraction, resulting in energy generation that allows the lower limb to advance. Also, it is a strategy designed to preserve balance, and, at the same time, to guarantee forward progression (Neptune et al., 2001; Neptune et al., 2008).

Due to their higher P1COF and V1COF values, subjects with PD and freezing are able to reach P2COF values that are closer to those of healthy gait. P2COF is predicted by the push-off PWR. The clinical implications of the correlation between RCOF and ankle push-off PWR warrant further consideration given the functional importance of ankle plantarflexors during gait. Adequate ankle control during gait is important for a normal gait pattern. Ankle power generation at push-off accounts for approximately 80% of the overall energy generated in the gait cycle of healthy subjects (Winter, 1983). This muscle group is also important for enabling elderly people to keep taking large steps (Judge et al., 1996). Moreover, reduced push-off PWR has been associated with unexplained falls and reduced speed in elderly people (Studenski et al., 1991). Based on these results, our hypothesis is that if people with PD are not able to sufficiently activate their plantarflexors to provide an efficient high amplitude power burst at push-off, they will be more susceptible to slips and/or falls.

The importance of this push-off deficit has been shown previously (Judge et al., 1996), with plantarflexor power generation described as the strongest predictor of reduced stride length in elderly subjects. The weakness of plantarflexor muscles, which show reduced electromyography activity in PD subjects, may be one of the causes of decreased push-off PWR (Dietz et al., 1997). Another cause of reduced push-off PWR may be muscle rigidity, which is a predominant feature of PD (Scandalis et al., 2001).

In conclusion, the results of the present study highlight the biomechanical strategies adopted by subjects with PD and FOG in order to walk on a supporting surface while in the OFF-pharma phase. These strategies are reflected in the following findings:

1-It is well known that the reduction of speed gait reduces the friction at loading response (P1COF) for healthy subjects. However, our results showed that, despite the lower gait speed of PD compared to HG, PD subjects presented higher P1COF values at loading response, probably due to the festinate gait pattern;

2-This fact might be associate to falls by tripping, when excessive or unexpected higher friction can lead to fall.

3-This fact also revealed that RCOF is a very sensitive variable to analyze festinating gait.

Neurorehabilitators and neurologists may benefit from the findings of this study because the RCOF is a simple variable to acquire and, as demonstrated in this study, can be used as a predictor of gait quality. Furthermore, RCOF analysis is readily applicable, given that the patient is not required to change clothes for the positioning of markers, simply being required to be barefoot.

Future studies shall measure the same subject under both ON and OFF medication conditions in order to better characterize RCOF during parkinsonian gait. This comparison would allow dissociation of the effects of levodopa from the basic motor disorder and would shed light on the physiological (or pathophysiological) significance of RCOF in PD patients with FOG. Moreover, future studies will be developed to explore the interplay between RCOF and plantarflexor muscle electromyography activity in PD patients.

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