The coefficient of friction in Parkinson's disease gait

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Summary

This study aimed to characterize the coefficient of friction (COF) curves of patients with Parkinson's disease (PD) during barefoot gait and to evaluate the relationships between this variable and functional scales. Twenty-two subjects with PD (ON phase of levodopa) and 22 healthy subjects participated in this study. The participants walked barefoot along a pathway that went over two force plates embedded in the floor of the data collection room. The instantaneous COF was calculated as the ratio between the horizontal and vertical components of the ground reaction forces. Two-sample t-tests applied to every 1% of the support phase of the COF curve were used to compare the groups and to identify the phases in which the two groups were different. Specifically, three COF areas were computed: Area 1 (for the loading response phase), Area 2 (for the mid-stance phase) and Area 3 (for the terminal stance phase). Pearson's tests were applied to assess the associations between the COF curve areas and the clinical scales. The subjects with PD exhibited lower COF values during the loading response and terminal stance phases and higher COF values during the mid-stance phase compared with the control group. A strong positive correlation was observed between Area 1 and the Timed Up and Go Test (90.3%). In conclusion, the patients' COFs exhibited patterns that were different from those of the control group. Moreover, during the loading response phase, these differences were well-correlated with the Timed Up and Go Test scale data; Timed Up and Go Test data can be used to identify the risk of falls among PD patients.

KEY WORDS: coefficient of friction, fall, ground reaction forces, Parkinson's disease.

Introduction

Gait disturbances and instability are common among patients with Parkinson's disease (PD). The most significant consequences of this dysrhythmic and disturbed gait include falls, which often lead to functional dependence and impinge greatly on quality of life. The causes of falls are multifactorial; they can be due to individual limitations, environmental conditions and/or interactions of these factors.
In clinical gait evaluation, the support phase is defined as the period of time during which the foot is in contact with the ground (Sutherland et al., 1998). Stance has also been broken down into a succession of different subphases, namely loading response, mid-stance, terminal stance and pre-swing (Whittle, 1993).
Gait changes in persons with PD have been characterized by a longer foot-flat in stance phase (Stocchi et al., 2015). Although the literature contains many studies that have characterized Parkinson gait, particularly in terms of spatio-temporal and kinematic gait patterns (Morris et al., 1994, 1996, 1998, 2001, 2005), evaluation of a variable able to characterize or support phase could offer new insights into the gait characterization of these patients.
In the support phase, the friction required at the shoe-floor interface to support different types of human activities is termed the coefficient of friction (COF) (Kleiner et al., 2015a). To calculate the COF, ground reaction force (GRF) data collected during the participant's gait are required. The instantaneous COF is calculated as the ratio between the shear of the horizontal GRF components (resulting from the mediolateral and anterior-posterior GRFs) and the vertical GRF (Kleiner et al., 2014, 2015a, 2015b).
During walking, slips result from a loss of friction between the foot and the floor (Chang et al., 2012; Redfern et al., 2001). The COF is one of the most critical gait parameters for predicting the risk of slipping (Chang et al., 2012; Cham et al., 2001; Lockhart et al., 2003; Redfern et al., 2001; Tsai and Powers, 2009).
Accordingly, characterization of the instantaneous COF curve during gait in PD patients should provide some insight regarding the incidence of falls of this population. Also, characterizing the COF curves of PD patients and looking for correlations between specific COF areas and the most commonly used functional scales could be a very simple way of predicting fall incidence in patients with PD. Our aims were to characterize the COF curves of patients with PD during barefoot gait and to analyze the possible correlations of this variable with the outcomes of the most commonly used functional scales for the evaluation of PD, i.e., The Six-Minute Walk Test (6MWT), the Timed Up & Go Test (TUG), the Unified Parkinson's Disease Rating Scale (UPDRS), and the Hoehn and Yahr Scale (HY).

Materials and methods

The study was approved by the Ethics Research Committee of the IRCCS San Raffaele Institute and written informed consent was obtained from the patients.

Participants

The PD group consisted of 22 patients affected by PD (9 females and 13 males). The average characteristics of the PD group were the following: age = 67.22±6.70 years; weight = 76.5±18.83 kg; height = 161.59±11.01 cm; UPDRS score = 45.92±28.68; and HY score = 2.76±0.788. PD diagnosis was based on clinical criteria (Gelb et al., 1999; Nutt and Wooten, 2005), dopamine transporter (DaT) scans and/or magnetic resonance imaging. The patients were similar in terms of disease duration, and according to their reported histories, symptoms, physical examinations and routine tests, they were free of peripheral sensory neuropathy and other disorders. Patients with primary parkinsonisms such as multiple system atrophy were not included in this study sample. Patients with liver, kidney, lung or heart disease, diabetes or other causes of autonomic dysfunction were also excluded.
The control group (CG) consisted of 22 healthy adults (9 females and 13 males) with the following average characteristics: age = 66.27±6 years; weight = 73.22±11.45 kg; and height = 164.81± 10.10 cm.

Data collection

All testing of the PD patients was performed in the ON phase during their best motor conditions, approximately 90 minutes after the first dose of levodopa in the morning.

Clinical assessments

Trained professionals performed all the instrumental and clinical assessments. The clinical and instrumental outcomes were assessed using valid and reliable tools for PD that included the following:
- the Six-Minute Walk Test (6MW): this is used to measure the maximum distance that a person can walk in 6 minutes (Steffen et al., 2002);
- the Timed Up & Go Test (TUG): this is a clinical measure of balance in elderly people and it is scored on an ordinal scale from 1 to 5 based on an observer's perception of the performer's risk of falling during the test (Rockwood et al., 2000; Steffen et al., 2002);
- the Unified Parkinson's Disease Rating Scale (UPDRS): this is a scale that is used to monitor PD-related disability and impairment (Song et al., 2009). The UPDRS is applied in 4 parts: UPDRS1 evaluates mentation, behavior and mood; UPDRS2 evaluates activities of daily living; UPDRS3 evaluates the patient's motor symptoms; and, UPDRS4 evaluates complications of therapy. In this study the four parts of the UPDRS were compared with the COF variables;
- the Hoehn and Yahr scale (HY): this is a commonly used system for describing how the symptoms of PD progress (Hoehn and Yahr, 1967).

Experimental procedures for motion analysis

The participant was instructed to walk barefoot at a self-selected speed along a pathway that went over two force plates (model 9286BA, Kistler Biomechanics, Switzerland) embedded in the floor of the data collection room. These plates collected data at a frequency of 500 Hz. The participants were aware of the positions of the force plates. A single trial was performed. The possible effects of the participant's chosen walking speed in the COF were measured by the contact time duration. The contact time was also calculated, as the time elapsing between heel strike and toe off, and it is expressed in seconds. No significant group-related differences were found (p=0.162).
During locomotion, the action forces exerted by the feet on the ground are counteracted by reaction forces that provide propulsion and equilibrium control. Analyses of GRF curves during locomotion can therefore provide valuable information about basic locomotor mechanisms and provide data that can be used to evaluate normal and pathological gaits. These forces can be separated into vertical, anterior-posterior and mediolateral direction components and can be measured with a force plate.
Data acquisition was performed using a Smartanalyser (BTS, Italy). The raw kinetic data were filtered using a second-order low-pass digital Butterworth filter with a cut-off frequency of 10 Hz. An algorithm developed in MATLAB (R2015b, MathWorks, Massachusetts USA) was used to filter the raw data and calculate the dependent variables. The GRF data from the force plates were normalized by the subjects' body weights and are expressed as percentages of the support phase. First, the COF curve was calculated as the ratio of the shear force to the normal GRF during standing (Chang et al., 2012; Redfern et al., 2001) as described in Equation 1.

$$COF = \frac{\sqrt{(F\gamma)^2 + (FX)^2}}{FZ} \quad (1)$$

where FY is the anterior-posterior GRF, FX is the mediolateral GRF, and FZ is the vertical GRF.
Comparisons of the COF curves of the PD group with those of the CG revealed differences during the loading response, mid-stance and terminal stance phases. As shown in Figure 1, the COF patterns of the PD patients were characterized by diminished values during the loading response and terminal stance phases and increased values during the mid-stance phase. To quantify these behaviors, the areas of the curves of each patient with PD and the average curves of the CG were calculated as illustrated in Figure 1 and described in Equation 2.

$$\text{Area} = \int_b^a [f(x)-g(x)]dx \quad (2)$$

where f(x) is the average COF curve of the CG, and g(x) indicates the COF curve of each patient with PD. Specifically, three COF areas were computed: Area 1 (for the loading response phase), Area 2 (for the mid-stance phase) and Area 3 (for the terminal stance phase).

For the statistical analyses, the data were first tested for normality using the Kolmoronov-Smirnov test. Since all the behavioral data exhibited normal distributions, para-

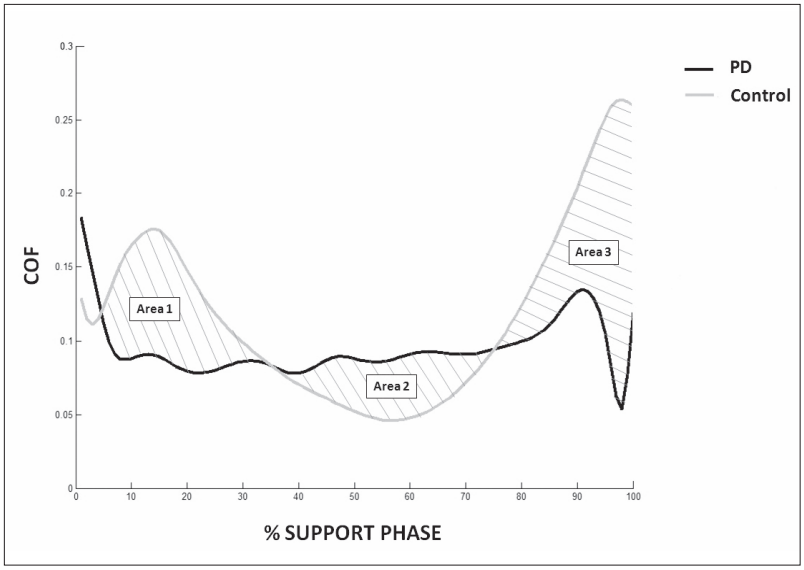

Figure 1 - Example of a COF curve of a PD patient (black line), the average curve for the entire control group (gray line) and the three phases in which the areas between the curves were calculated.

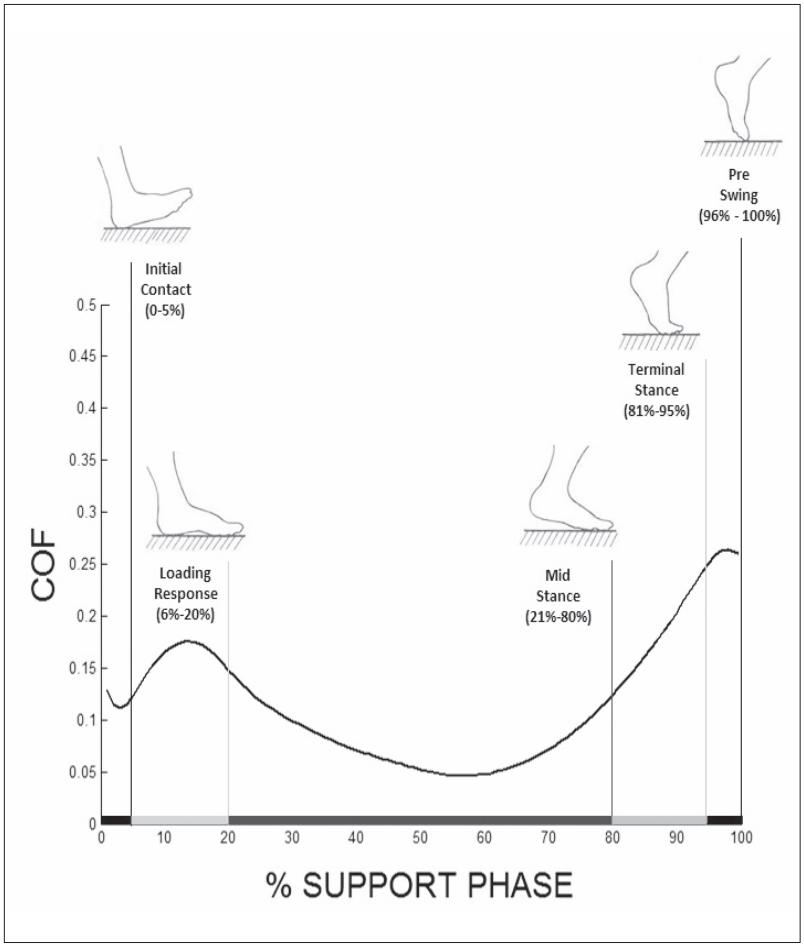

Figure 2 - The phases of the support phase.

metric statistics were applied. First, one-way ANOVAs ($\alpha \leq 0.05$) were applied to compare the anthropometric data (i.e., age, body weight and height) between the PD group and the CG. This test was also applied to compare the differences between the right and left lower limbs in the PD group and the CG. Because no significant differences were found between the right and left limbs, the left limb was selected to represent the CG and PD hemi-bodies for all curve comparisons.

Comparisons between the mean COF curves of the PD patients and the CG were performed using two-sample t-tests ($\alpha \leq 0.05$), which were applied to every 1% of the gait cycle. For this analysis the sub-phases of the support phase were defined as follows (Whittle, 1993): initial contact (0-5% of the support phase); loading response (6-20% of the support phase); mid-stance (21-80% of the support phase); terminal stance (81 to 95% of the support phase); and pre-swing (96 to 100% of the support phase). Figure 2 illustrates these sub-phases of the support phase.

Next, Pearson's correlations ($\alpha \leq 0.05$) were used to assess associations between the COF curve areas and the outcomes of the functional scales: HY, UPDRS, TUG and 6MWT. In accordance with Taylor (1999), the correlations were interpreted as follows: 0.9 to 1 indicated a very high correlation; 0.7 to 0.9 indicated a high correlation; 0.5 to 0.7 indicated a moderate correlation; 0.3 to 0.5 indicated a low correlation; and 0 to 0.3 indicated little to no correlation. All tests were two-tailed. SPSS (version 19, IBM, Armonk, New York, United States) was used to perform all statistical analyses.

Results

A one-way ANOVA revealed no significant differences between the PD subjects and the CG in age ($F_{1,20}=0.272$; $p=0.605$), body weight ($F_{1,20}=0.485$; $p=0.490$) or height ($F_{1,20}=1.026$; $p=0.371$).

The COF curve analyses identified three phases during the support phase in which the PD pa-

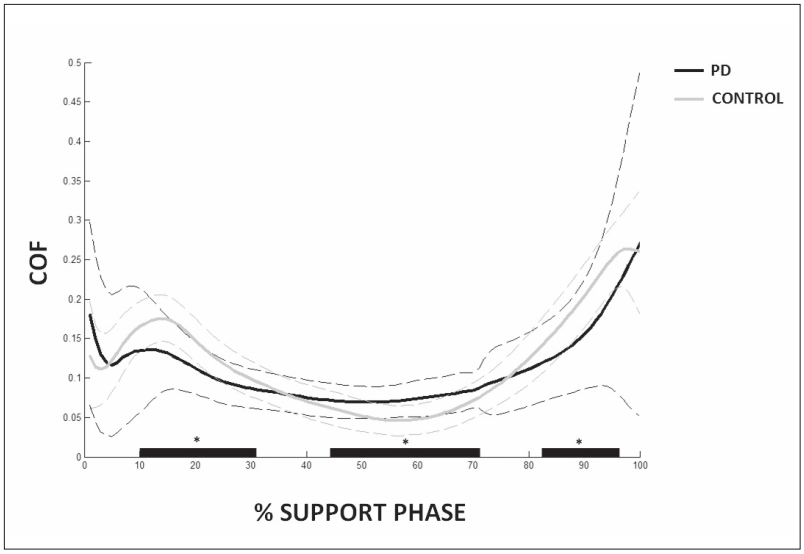

Figure 3 - Mean values and standard deviations of the COF curves of the Parkinson's disease group and the control group.
PD group - solid black line: mean; dashed black lines: standard deviation. Control group - solid gray line: mean; dashed gray lines: standard deviation. The bars and asterisks on the x-axes indicate the instants of the support phase that exhibited significant differences ($p \leq 0.05$) between the PD and control group curves. Legend: PD = Parkinson's disease group; CONTROL = control group; %SUPPORT PHASE = normalized to the percentage of the support phase.

tients exhibited alterations compared with the CG: during the loading response phase to the beginning of the mid-stance phase (10 to 31% of the support phase); during the mid-stance phase (45 to 71% of the support phase), and during the terminal stance phase (81 to 95% of the support phase). Figure 3 illustrates these results.
COFs were found to be higher near the loading response and terminal stance phases in the CG, and this pattern was not observed in the PD group.
A very high correlation was observed between Area 1 and the TUG outcomes ($\rho = 0.903$). Furthermore, moderate correlations were found between Area 1 and UPDRS1 ($\rho = 0.505$); between Area 1 and 6MWT ($\rho = -0.672$); and between Area 2 and UPDRS2 ($\rho = 0.515$) and UPDRS4 ($\rho = 0.512$). Table I presents these results.

Discussion

This study aimed to characterize the COF curves of patients with PD in the ON levodopa stage during gait and to evaluate the relationships between this index and functional scales.
First, it is important to understand the meaning of the COF in gait. The shear forces are highest near the loading response and terminal stance phases (Chang et al., 2012). These are the instants at which slips most often occur. The initial contact seems to be the critical phase in which slips can result in falls in patients with PD. The loading response causes forward slips on the leading foot, whereas the terminal stance causes backward slips on the forepart of the sole, which can more easily be counteracted by stepping forward with the leading foot (Redfern et al., 2001). Thus, the friction that occurs during the loading response is critically important for determining whether the frictional capabilities of the foot-floor interface will be sufficient to prevent slips in PD patients.
The results of this study indicate that more severely affected PD patients exhibit lower COF area values during the loading response phase. Moreover, when the COF curves of the PD group were compared with those of the CG, the PD patients exhibited lower COFs during the loading response and terminal stance phases and higher COF values during the mid-stance phase. This behavior might be explained by the flat foot contact that has been observed during parkinsonian gait (Morris et al., 1994, 1996, 1998, 2001, 2005), and it is likely related to the need to increase safety margins (Morris et al., 2001, 2005). Another possible explanation is related to the typical speed reductions that have previously been reported in PD subjects (Morris et al., 1994, 1996, 1998, 2001, 2005). Both these factors, among others, might have contributed to the kinematic and dynamic alterations in the gait patterns of the PD patients that were revealed through examination of their COF curves. It would be interesting, in future studies, to determine the particular contribution of each of these factors.
A very high correlation was observed between Area 1 and TUG, with higher Area 1 COFs found to be associated with longer times required to perform the TUG. Turning is an essential part of goal-directed locomotion that people engage in daily (Stack et al., 1994). However, turning difficulty is a common problem in people with PD (Stack et al., 1994). A previous study noted that more than 50% of patients with PD have difficulty turning that can lead to falls (Stack et al., 1994). Mak and Pang (2009) noted that the TUG can be used to distinguish fallers from non-fallers; a longer TUG time (16 seconds) is independently associated with an increased risk of falls in patients with PD.
The present study also found that the greater the area during the loading response (Area 1), the shorter the distance covered during the 6MWT by the patients with PD. It seems that the COF during the loading response phase was influenced by gait velocity in the PD patients. Moreover, in the loading response phase, the patients with PD exhibited increases in Area 1 that scaled with increases in cognitive decline (UPDRS1).
Cognitive decline is another independent risk factor for falls (Herman et al., 2010; Mirelman et al., 2012). Gait disorders and falls are more prevalent among demented patients than non-demented subjects, and there is a direct relationship between the severity of cognitive impairment and increased gait abnormalities (Amboni et al., 2013; van Iersel et al., 2004). Gait is no longer merely considered an automated motor activity, but rather an

Table I. Correlations of the COF areas of the PD patients with the outcomes of the functional scales (Pearson's tests, $P < 0.05$).

VARIABLES		Area1	Area2	Area3
$UPDRS_{total}$	ρ	0.077	0.043	-0.065
	P	0.755	0.862	0.791
$UPDRS_1$ – Mentation, behaviour and Mood	ρ	0.505	0.345	0.059
	P	0.046	0.191	0.827
$UPDRS_2$ – Activities and Daily Living	ρ	0.451	0.515	0.040
	P	0.080	0.041	0.882
$UPDRS_3$ – Motor Examination	ρ	0.488	0.105	-0.106
	P	0.055	0.699	0.696
$UPDRS_4$ – Complications of Therapy	ρ	-0.050	0.512	-0.179
	P	0.853	0.043	0.507
H&Y	ρ	0.249	0.461	0.115
	P	0.370	0.084	0.682
TUG	ρ	0.903	0.368	-0.035
	P	0.0001	0.161	0.896
6MW	ρ	-0.672	-0.095	-0.029
	P	0.004	0.726	0.914

activity that requires executive function, attention, motivation and judgment of external and internal cues (Yogev-Seligmann et al., 2008).

Given these associations and the effects of cognitive impairment and gait abnormalities on functional independence, our results highlight the multiple links between gait, cognitive function, COF and falls.

During the mid-stance phase, the PD patients exhibited higher COFs than did the CG subjects. Furthermore, these mechanisms (Area 2) were correlated with activities of daily living (UPDRS2) and complications of therapy (UPDRS4) in the PD patients. The proposed approach of observing the COF during gait revealed a compromise between decreased efficiency in favor of increased safety during parkinsonian gait.

Finally, to improve COF characterization during parkinsonian gait, future studies should compare this variable between the levodopa ON and OFF stages. This comparison would allow a dissociation of the effects of levodopa from the basic motor disorder and may shed light on the physiological (or pathophysiological) meanings of COFs in patients with PD.

In conclusion, the COFs measured in the patients with PD exhibited a specific pattern of differences when compared with those of the CG; during the loading response phase, the difference was well correlated with the TUG data, identifying the risk of falls among patients with PD. The present analysis represents an initial first attempt to evaluate a gait analysis parameter in terms of its utility in the prediction of the real fall propensity of patients with PD. Furthermore, COF analysis is readily applicable, given that the patient is not required to change clothes for the positioning of markers and is only required to be barefoot. Therefore, the patient can be evaluated easily during both the OFF and ON medication stages.

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