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Slip avoidance strategies in children with bilateral spastic cerebral palsy and crouch gait

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ABSTRACT

Background: A slip occurs when the required friction (RCOF) to prevent slipping at the foot/floor interfaces exceeds the available friction. The RCOF is dependent upon the biomechanics features of individuals and their gait. On the other hand, the available friction depends on environmental features. Once individuals with crouch gait have their biomechanics of gait completely altered, how do they interact with a supporting surface? The aim was to quantify the RCOF in children with bilateral spastic cerebral palsy (BSCP) and crouch gait.

Methods: 11 children with crouch gait and 11 healthy age-matched children were instructed to walk barefoot at self-selected speed over a force platform. The RCOF curve was obtained as the ratio between the tangential forces (FT), and the vertical ground reaction force (FZ). Three points were extracted by the RCOF, FT and FZ curves at the loading response, midstance and push-off phases.

Findings: Children with BSCP presented higher values of RCOF in all support phase and lower gait velocity relative to the healthy controls. For BSCP group no correlation between FT and FZ were found, indicating that this group is not able to negotiate the forces during the support phase.

Interpretation: Children with BSCP and crouch gait are not able to negotiate the forces applied on the ground in support phase, so to avoid the fall, their strategy is to reduce the gait velocity.

1. Introduction

Cerebral palsy (CP) describes a group of permanent disorders of the development of movement and posture causing activity limitation that are attributed to non-progressive disturbances that occurred in the brain before or at birth (Morris, 2009; Rosenbaum et al., 2007). Bilateral spastic CP (BSCP), affects bilaterally the lower extremities more than the upper extremities in most cases. Crouch gait, one of the most common gait pathologies in patients with BSCP (Wren et al., 2005), is characterized by increased knee flexion throughout stance phase and, frequently, increased hip flexion and internal rotation (Rodda et al., 2004). The crouch gait progressively worsens over time, decreasing walking efficiency and leading to joint degeneration (Hicks et al., 2008). Moreover, crouched postures reduce the capacity of muscles to extend the hip and knee during the single limb stance phase of gait (Hicks et al., 2008) and may delay the ability to walk independently or cause tripping, falling and functional impairment (Goldstein and Harper, 2001; Rab, 1992).

A slip occurs when the required coefficient of friction (RCOF) to prevent slipping at the foot/floor interfaces exceeds the available friction (Chang et al., 2011; Redfern et al., 2001). The RCOF depends on individual and gait biomechanics features; while the available friction depends on environmental features, such as the tribology of shoes/foot soles and supporting surface characteristics (Chang et al., 2011; Redfern et al., 2001). The RCOF is calculated as the ratio of the tangential (FT – Fig. 1b) to the vertical ground reaction force (FZ – Fig. 1a) during stance phase (Chang et al., 2011; Redfern et al., 2011). During walking the FT applied to the floor cannot exceed the FZ, if it happens, a slip or a fall will occur (Redfern et al., 2011). So, the correlation between FT and FZ is an interesting tool to detect which phase of the stance is more critical to lead the children with BSCP to a fall or slip; or to observe which strategy is adapted by these patients to avoid the imbalance.

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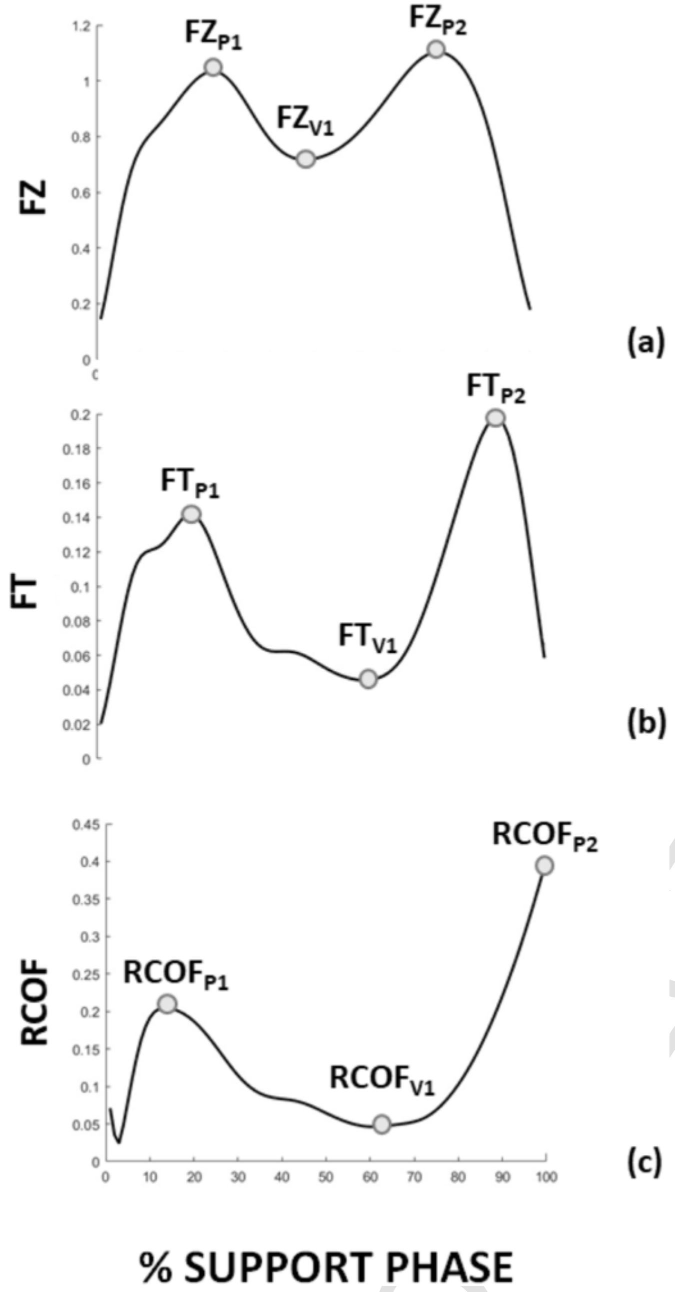

Fig. 1. Illustration of FZ (a), FT (b) and RCOF (c) curves of one child of the reference group.

The RCOF curve is characterized by two peaks and one valley (Fig. 1c). The two peaks indicate the phases where the shear forces are higher and occur, respectively, at the loading response phase and the push-off phases (Chang et al., 2011). These are the moments when slips are more likely to occur (Chang et al., 2011; Redfern et al., 2001). Additionally, the valley is observed in the mid-stance phase (Kleiner et al., 2015b; Kleiner et al., 2017; Pacifici et al., 2016). The lower the value of the valley, the higher the lower limb joints range of motion (Kleiner et al., 2015b; Kleiner et al., 2017; Pacifici et al., 2016).

The RCOF has already been quantified in elderly (Anderson et al., 2014; Kleiner et al., 2015b) and in subjects with Parkinson's disease, stroke and multiple sclerosis (Kleiner et al., 2014; Kleiner et al., 2015a; Kleiner et al., 2017; Pacifici et al., 2016), where the strategies used by these populations to avoid a slip or a fall were described. Subjects with Parkinson's disease, thanks to their shuffling gait pattern, presented lower RCOF values in loading response and push-off phases and higher RCOF values during mid-stance phase when compared to healthy controls (Kleiner et al., 2017). The impaired ankle range of motion control in subjects with multiple sclerosis causes an increased RCOF in the push-off phase when compared to a reference group (Pacifici et al., 2016). The stroke affected and non-affected lower limbs presented higher RCOF values at midstance and push-off phases compared to the reference group; this behavior can be explained by the stroke patients dropped foot (Kleiner et al., 2014; Kleiner et al., 2015a).

However, this parameter has never been quantified in a pediatric population. Thus, the aim was to quantify the RCOF in children with BSCP and crouch gait. The complete description of the RCOF parameters could bring us new insights about the crouch gait related kinetics, helping to identify the most critical support phase instants that could lead this population in a slip or a fall.

2. Methods

2.1. Participants

Eleven children with bilateral spastic cerebral palsy (BSCPG) were involved in this study. The inclusion criteria were: (a) children with the diagnosis of BSCP in the prenatal, perinatal or postnatal period; (b) aged between 6 and 12 years old; (c) cognitively competent and able to understand and follow instructions; (d) able to walk independently and without walking aids; (e) no history of upper or lower limb functional surgeries and of pharmacological treatments received during the last past year or within the period of study; (f) Gross Motor Function Classification System level 2 (Palisano et al., 2008); (g) had no orthopaedic conditions or fixed deformities that interfere with lower limb functions; and, (h) present crouch gait according to Rodda et al. (2004). As reference group, additional 11 healthy children, paired by age, were selected from our data base and evaluated. Table 1 presents the sample characteristics.

Written informed consent was obtained from the parents and/or guardians of the children prior to their enrolment in this study, which was conducted in compliance with the current revision of the Declaration of Helsinki and the Good Clinical Practice Guidelines.

2.2. Experimental procedures

Data collection was performed at the motion analysis laboratory of IRCCS San Raffaele Pisana, Rome (Italy), using an optoelectronic system involving 12 infrared cameras (Elite 2002, BTS, Milan, IT) with a sampling rate of 100 Hz, synchronized with 2 tri-axial force platforms (Kistler, CH) with a sampling rate of 500 Hz, and with 2 TV camera video recording systems (Video System, BTS, Italy). For data acquisition, 1 spherical retro-reflective passive marker (14 mm diameter) was

Table 1
Mean and standard deviation of the anthropometric data.

Variables	Reference group	BSCP group	Comparison
N	11	11	–
Age (years)	8.13 (2.47)	7.82 (2.52)	$t_{20} = -0.264$; $p = 0.795$
Weight (kg)	35.81 (10.58)	30.09 (13.09)	$t_{20} = -1.128$; $p = 0.273$
Height (cm)	1.39 (0.17)	1.28 (0.17)	$t_{20} = -1.291$; $p = 0.214$
Body Mass Index ($kg \cdot m^{-2}$)	17.50 (2.86)	16.66 (2.70)	$t_{20} = -0.649$; $p = 0.525$

placed on the child sacrum. Based on the displacement of this marked the gait mean velocity (m/s) was calculated.

The subjects were asked to walk at their self-selected speed, barefoot, along an 8-meter parquet pathway and at least six walking trials were recorded. All the data acquisition procedures were performed in the same day. The trails in which we were able to acquire the kinetic data were considered for the analysis. So, at least 3 trials were used to calculate the variables and, for the statistical analysis, the average value was calculated considering all the trials. It was considered a representative datum for each participant and, therefore, it was used in our correlation analysis.

2.3. Data analysis

The raw kinetic data were filtered using a 2nd order low-pass digital Butterworth filter with a cutoff frequency of 10 Hz. An algorithm developed in MATLAB was used to filter the raw data and to calculate the dependent variables. The ground reaction force data from the force plates were normalized by the subjects' body weights and are expressed as percentages of the support phase.

To compute the RCOF the first step was to calculate the tangential force (FT - Fig. 1b). It was computed as the resultant sum of FX (lateral GRF) and FY (anterior-posterior GRF) as shown in Eq. (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 – Fig. 1a) during standing – Eq. (2):

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

As the walking speed directly affects the magnitude of shear force, we expect a direct effect on RCOF too (Kim et al., 2005); for this reason, the RCOF parameters were normalized by the subject mean velocity.

Once computed the RCOF, some discrete variables were identified: (a) RCOF$_{P1}$: the local maximum of the RCOF curve occurring at about 10 to 20% of the stance phase in the loading response phase (Chang et al., 2011 – Fig. 1c); (b) RCOF$_{P2}$: another local maximum occurring at ~90% in the push-off phase (Chang et al., 2011 - Fig. 1c); (c) RCOF$_{V1}$: the minimum value of RCOF during the midstance phase (Kleiner et al., 2015a; Kleiner et al., 2017 - Fig. 1c).

As FZ and FT are characterized by two peaks and one valley (Fig. 1a and b), we also calculated the following discrete variables: first peak of impact (FZ$_{p1}$ and FT$_{p1}$), maximum value of first curve peak; valley (FZ$_{v1}$ and FT$_{v1}$), minimum value between the first and the second peak of the vertical component curve; and the propulsion peak (FZ$_{p2}$ and FT$_{p2}$), maximum value of the second curve peak.

2.4. Statistical analysis

Since the data exhibited normal distributions (Kolmogorov-Smirnov test) and homogeneity (Levene's statistic), parametric statistics were applied. First, the *t*-test was applied to compare the anthropometric data (i.e., age, body mass and height) between the BSCP and the control groups. Also, the *t*-test was applied to compare the differences between groups for the dependent variables. Comparisons between the mean RCOF curves of the BSCP and the control groups were performed with two-sample *t*-tests that were applied to every 1% of the support phase. Finally, the Pearson Correlation was used to assess the associations between the GRF tangential (FT) and normal components (FZ) separately per group. For all comparisons, an α value of 5% was considered significant. The statistical analysis was performed using the IBM SPSS Statistics v.22 software (IBM, Armonk, NY, USA).

3. Results

No differences between groups (BSCP and Reference) were found for age, weight, height and BMI. The anthropometric characteristics are shown in Table 1.

The RCOF curve analyses showed that differences between groups were present during all support phase. Fig. 2 illustrates these results. The analysis of the discrete variables confirmed the results of the RCOF curves comparison, where the BSCP group presented higher values of ROCF$_{P1}$, RCOF$_{V1}$ and RCOF$_{P2}$ in comparison with the control group (see Table 2). Also, the BSCP group presented higher values of FZ$_{v1}$ and FT$_{v1}$; and, lower FZ$_{p2}$ and gait speed.

Finally, for the reference group the Pearson correlation analysis revealed high positive correlations between FT$_{p1}$ and FZ$_{p1}$ ($r = 0.943$;

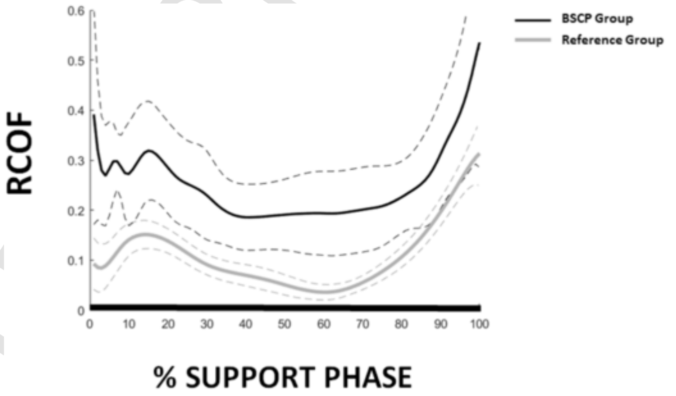

Fig. 2. Means and standard deviations of the RCOF curves normalized by the gait speed of the BSCP group (black solid line: mean; black dashed line: standard deviation) and the reference group (grey line: mean; grey dashed line: standard deviation). In all support phase instants, the curves were significantly different ($p \leq 0.01$). Legend: %SUPPORT PHASE = normalized to the percentage of the support phase.

Table 2
Mean and 95% confidence interval (lower endpoint and upper endpoint) of FZ, FT and RCOF normalized by the gait speed for reference and BSCP groups.

Variables	Reference group	BSCP group	Comparison
Gait speed (m/s)	1.07 (1.00–1.15)	0.61 (0.49–0.74)	$t_{20} = -6.958$; $p = 0.001$*
FZp1	1.07 (1.02–1.13)	1.11 (0.98–1.25)	$t_{20} = 0.633$; $p = 0.534$
FZv1	0.76 (0.70–0.82)	0.85 (0.77–0.94)	$t_{20} = 2.112$; $p = 0.047$*
FZp2	1.04 (0.99–1.09)	0.96 (0.91–1.01)	$t_{20} = -2.649$; $p = 0.015$*
FTp1	0.15 (0.13–0.17)	0.17 (0.11–0.23)	$t_{20} = 0.860$; $p = 0.400$
FTv1	0.02 (0.02–0.03)	0.09 (0.07–0.11)	$t_{20} = 6.1760$; $p = 0.001$*
FTp2	0.17 (0.15–0.19)	0.15 (0.10–0.19)	$t_{20} = -1.149$; $p = 0.264$
RCOFp1	0.15 (0.14–0.17)	0.49 (0.29–0.70)	$t_{20} = 3.731$; $p = 0.001$*
RCOFv1	0.03 (0.02–0.04)	0.16 (0.13–0.20)	$t_{20} = 7.975$; $p = 0.0001$*
RCOFp2	0.31 (0.28–0.34)	0.58 (0.41–0.74)	$t_{20} = 3.488$; $p = 0.002$*

* A statistical significant difference ($p < 0.05$) between reference group and BSCP group.

$p = 0.0001$); and between FT_{p2} and FZ_{p2} ($r = 0.855$; $p = 0.0001$). However, no correlation was observed between FT_{v1} and FZ_{v1}. Still, no correlations between FT and FZ were observed for the BSCP group.

4. Discussion

Children with BSCP present higher values of RCOF relative to the healthy controls during all the stance phase. The higher RCOF peaks ($RCOF_{P1}$ and $RCOF_{P2}$) and valley ($RCOF_{V1}$) values maybe due to the reduced range of motion in the lower limb joints (Hicks et al., 2008; Nordmark et al., 2009; Rodda et al., 2004; Thomason et al., 2015; Wichers et al., 2009). The crouch gait is characterized by increased dorsiflexion and knee flexion throughout the stance phase and, frequently, increased hip flexion and internal rotation (Hicks et al., 2008; Rodda et al., 2004). The crouched posture significantly reduces the capacity of muscles to extend the hip or knee joints, individuals may be required to exert more muscle force to maintain a crouched posture (Hicks et al., 2008).

The correlation analysis for the reference group showed that, at the loading response and push-off phases, the higher the tangential force (FT), the higher the vertical component (FV). This correlation may be seen as a strategy implemented for minimizing the effects of the increment of the tangential force. However, as expected, in the midstance phase no correlation between FV and FT was observed. Indeed, in the midstance of normal gait the FZ and FT forces are reduced (see Fig. 1a and b) allowing, respectively, the deceleration for loading and the acceleration for guaranteeing the gait progression.

In the BSCP group no correlations between FT and FZ were found, indicating that this group was not able to negotiate the forces during the support phase. Since our results showed that the gait speed of the BSCP group was reduced in comparison with the reference group, we can infer that the strategy adopted by children with BSCP and crouch gait to avoid a fall is to reduce the gait speed to do not overload the forces during the loading response and push-off phases.

Given the reduced number of analyzed children with BSCP, future analyses should be conducted on an increased sample size, also considered the increased variability of force platform data in children with cerebral palsy compared to healthy controls (Steinwender et al., 2000; White et al., 1999). Moreover, CP is a very heterogeneous diagnosis, even BSCP where several gait pathological types have been identified (Rodda et al., 2004). This paper studied only children with BSCP and crouch gait with mild gait impairments, and can only form conclusions on this group. Future studies aiming to evaluate the RCOF in CP may be conducted focusing on children with CP with greater gait deviation/more severe symptoms.

In conclusion, children with BSCP and crouch gait are not able to negotiate the forces applied on the ground in support phase, so to avoid the fall, their strategy is to reduce the gait velocity. This 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 children with BSCP. Furthermore, the analysis of the RCOF can be easily performed because the patient is not required to change clothes for the positioning of markers and is only required to be barefoot.

Nomenclature

CP	cerebral palsy
BSCP	bilateral spastic cerebral palsy
RCOF	required coefficient of friction
$RCOF_{P1}$	RCOF in loading response phase
$RCOF_{V1}$	RCOF in midstance phase
$RCOF_{P2}$	RCOF in push-off phase
FT	tangential forces
FT_{P1}	tangential forces in loading response phase
FT_{V1}	tangential forces in midstance phase
FT_{P2}	tangential forces in push-off phase
FZ	vertical ground reaction force
FZ_{P1}	FZ in loading response phase
FZ_{V1}	FZ in midstance phase
FZ_{P2}	FZ in push-off phase

Conflict of interest

None of the authors has conflicts of interest concerning this study.

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