Length of the Center of Pressure Plot: Technique for Quantifying Gait Performance

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Abstract – **Using information about the values of the total center of pressure (CoP) and total vertical ground reaction force (GRF) during gait, quantitative parameters based on CoP trajectory length and trajectory length of 3-D plot of vertical GRF vs. CoP can be calculated and used to compare pathological prosthetic gait and normal gait. Seven patients with right transtibial amputation using passive transtibial prostheses, and ten healthy subjects participated in the study. After calculating the parameters of each patient and healthy subject, the two-sample t-test was used to assess the significance of the differences between the results of the two groups. Also, the observed parameters were compared with each other. For this purpose, Pearson correlation coefficients between the parameters were calculated to study the relationships between the parameters. The results show that in all cases, the parameters described in patients are significantly different than in healthy subjects. New parameters provide new information on way of walking and show the differences in gait step as a whole. The described techniques and calculated and statistically evaluated values of proposed parameters can be used for gait analysis in clinical practice.**

Keywords- gait, center of pressure, ground reaction force, CoP displacement, trajectory length

I. INTRODUCTION

In clinical practice, force platforms are used for measurement and calculation of the ground reaction force (GRF) under the feet and the center of pressure (CoP) position, [1]. One can use a force platform, on which the subject stands or walks with their both feet, to examine the GRF or CoP of the whole body and calculate other movement parameters, [2]. Currently, platforms are used for recording the forces exerted by each foot and examining the trajectory of CoP under each foot separately, [2]-[4]. Generally, platforms are not used to calculate the total CoP position during walking. If it is necessary to evaluate gait as a whole and focus on gait patterns, motion capture (MoCap) systems (e.g. camera systems, accelerometer systems, etc.) are usually used to study the gait. However, these systems for studying gait as a whole are rather expensive, and therefore only specialized laboratories are equipped with these. In the case of the evaluation of walking gait as a whole with larger, especially wide base of support using two or three low cost force platforms, only very few proposals of evaluation method have been presented. Thus, the objective of this article is to describe methods of the evaluation of the total CoP over whole gait step which has not yet been used in practice and may lead to an increased application of the low cost force platforms for measurement of gait as a whole with larger, especially wide base of support. These methods will be based on methods already used in study of postural stability of standing, [5], have never been used in the past for the evaluation of total GRF or CoP over one gait step. The methods assume the calculation of the trajectory length of CoP displacement. The technique and proposed parameters could be used for gait analysis in clinical practice.

In the first part of article we describe the experiment, i.e. selection of participants and measurement devices. In the second part, the data processing and calculations are described. In the final parts of the article we statistically evaluate the data and describe results and potential application in clinical practice.

II. METHODS AND MEASUREMENT

A. Selection of participants

Seven patients (Pts) (aged 67.3 (SD 13.5) years; body weight 92.4 (SD 8.4) kg; height 176 (SD 3) cm) with right transtibial amputation (151 (SD 92) days after amputation) with passive transtibial prostheses participated in the study. The patients were recruited from the University Hospital Hradec Kralove. The patients were measured in the initial phase of the clinic's rehabilitation program. Ten healthy subjects (HS) (aged 31.9 (SD 10.4) years; body weight 68.3 (SD 9.3) kg; height 168 (SD 4) cm) were also recruited for a comparative analysis. Healthy subjects

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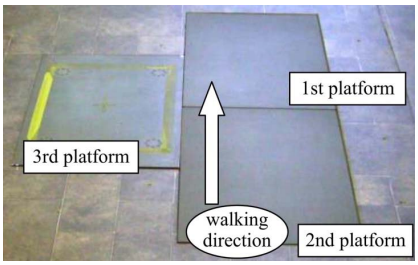
Figure 1. The force plates Bertec arranged in staggered configuration for study of the total CoP and total vertical GRF.



were recruited from among the students at Czech Technical University in Prague. The study was performed in accordance with the Helsinki Declaration. The study protocol was approved by the local Ethical Committee and the University Hospital

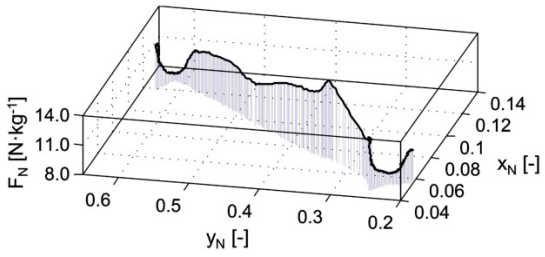
B. Measurement devices

For the study of CoP, three force plates FP4060-07 (Bertec Corporation, Columbus, Ohio, USA) with a sample frequency of 2000 Hz arranged in staggered configuration were used to record the CoP position and the vertical GRF. The platform and its software provide the information about vertical GRF (F_i) and CoP position ($p_i(x_i, y_i)$) according to the position of the coordinate system, [6]. The computational algorithm is based on formulas processes the dataset measured by three force platforms and information about the relative positions and geometric dimensions of the force platforms.

C. Test procedure

The force platforms were placed along the walkway. A custom-written program using computational algorithm written in MatLab software (MatLab R2010b, Mathworks, Inc., Natick, MA, USA) was used to calculate the total CoP and vertical component of total GRF. The stationary platforms were calibrated prior to every measurement, the value of force and CoP position were set to zero beforehand. The data were recorded with sampling rate of 340 Hz. The subjects performed two trials of barefoot walking along a 4 m walkway at a self-selected comfortable gait speeds. The mean walking speed was 2.13 (SD 0.20) km·h^{-1} in the case of the HS, and 0.96 (SD 0.21) km·h^{-1} in the case of the Pts. The speed was calculated from the length of the CoP trajectory in the direction of anteroposterior axis and the time of movement. While all healthy individuals were asked to walk at a slow speed, patients were asked to walk at comfortable self-selected speed. The low speed of walking can be justified by the fact that patients were still getting used to the prosthesis during the rehabilitation process. And the discrepancy in movement speed between Pts and HS can be explained by the naturally slow walk of patients after amputation, and also by the need to test whether the measured parameters has any relationship with the speed of movement. We obtained data for one step only which corresponded to the data span from the beginning of a single-support phase (typically at 0% of gait cycle) to the end of the next single-support phase of the opposite limb (more or less 50% of gait cycle).

Figure 2. Normalized CoP displacement vs. normalized vertical GRF over one step (50% of gait cycle).



D. Methods of the data analysis

To remove any effects that are attributable to body height or leg length, CoP displacements were normalized appropriately to each participant's height using the same methods as in previous works, [7],[8]. The normalization was performed for each difference between two consecutive values in a set of values, i.e. record, of the CoP positions in medial-lateral (M-L) and anterior-posterior (A-P) direction.

The novel method for the identification of pathological gait is based on well-known mathematical tools used in static posturography, [5],[9]. The total length of trajectory (d_{NCoP}) is used to evaluate a CoP plot. The total length of the trajectory of the CoP in the ground plane is computed by calculating the sum of the Euclidean distances between consecutive data points (i.e. Cartesian coordinates) in Euclidean 2-D space, [10], collected during the trial, given by [5]:

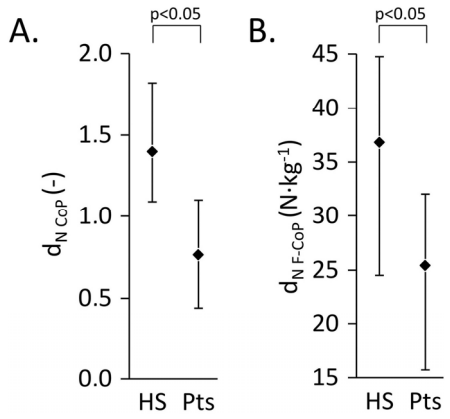
$$d_{NCoP} = \sum_{n=1}^{N} dist(P_n, P_{n-1}) = \\ = \sum_{n=1}^{N} \sqrt{\left(x_{N(n)} - x_{N(n-1)}\right)^2 + \left(y_{N(n)} - y_{N(n-1)}\right)^2} \quad (1)$$

in which $P_n=(x_{N(n)}, y_{N(n)})$ is the data point at time n and the $P_{n-1}=(x_{N(n-1)}, y_{N(n-1)})$ is the data point at time $n-1$. N is the number of sample points, [11]. x_N is the normalized CoP displacement in M-L direction, y_N is the normalized CoP displacement in A-P direction. The number of points is determined by the recorded length of the dataset determined by the interval between two successive peaks, i.e. maximum medial and maximum lateral CoP peak displacements (x_{Nmax}, x_{Nmin}), and the sampling frequency (340 Hz).

Further, GRF is normalized to the body mass, preventing the effect of the variability of different body masses of subjects, see [12],[13], and this normalized total GRF (F_N) was used for the gait evaluation. All three-above-mentioned measured and normalized variables - F_N, x_N, y_N – can be plotted vs. each other in a 3-D plot, see Fig. 2. The 3-D trajectory enables us to evaluate gait as a whole using GRF and CoP positions. Among many methods, the length of the trajectory of the 3-D plot ($d_{NF\text{-}CoP}$) can be used to describe the 3-D trajectory itself. The following formula uses the sum of Euclidean distances between consecutive data points in Euclidean 3-D space:

$$d_{NF-CoP} = \sum_{n=1}^{N} \sqrt{\left(x_{N(n)} - x_{N(n-1)}\right)^2 + \left(y_{N(n)} - y_{N(n-1)}\right)^2 + \left(F_{N(n)} - F_{N(n-1)}\right)^2} \quad . \quad (2)$$

Figure 3. Comparison of the CoP trajectory length (A.) and trajectory length of 3-D plot of vertical GRF vs. CoP (B.) of healthy subjects (HS) and patients (Pts)



The custom-written MatLab program based on the functions of the MatLab software was used to calculate d_{NCoP} and $d_{NF\text{-}CoP}$.

After calculating the parameters of each Pts and HS, the Jarque–Bera test was used to test the normal distribution of calculated parameters. The Mean, minimum (Min), maximum (Max) and the standard deviation (SD) were then used to present and compare the results. Also, the Two-sample t-test, was used to assess the significance of the differences between the Pts and HS. The significance level was set at $p<0.05$. The measured data were compared to identify the abnormal gait of Pts. Moreover, Pearson correlation coefficients between the parameters were calculated to study the relationships between the parameters. The analysis was performed using MatLab software.

III. RESULTS

We used the statistical data (Tab. 1) to illustrate the relationship between the calculated parameters of the HS and Pts. The Fig. 3 shows the minimum (Min), maximum (Max) and Mean of calculated parameters. The Jarque-Bera test returns zero in all cases. Since the data have normal distribution, the t-test was used to analyze them. Significant differences were found in the comparison between Pts and HS. The level of significance was lower than 0.001.

Pearson correlation coefficients between the parameters were also calculated to study the parameters, see Tab. 2 and Tab. 3. A strong correlation between the d_{NCoP} and $d_{NF\text{-}CoP}$ was identified only in the case of the Pts. In all other cases, the correlations between parameters were weak or very weak.

IV. DISCUSSION

The new quantitative methods are based on the plot of normalized CoP displacement and normalized CoP displacement vs. normalized GRF over one step. The results show that the described parameters in Pts with right transtibial amputation are significantly different than the parameters in HS, i.e. values are lower in the case of the Pts, see Fig. 3.

Regarding the walking speeds of Pts and HS, the Pearson's Correlation test was used to determine the relationship between parameters. The test showed a weak correlation between the parameters based on CoP trajectory and walking speedtaken that the CoP trajectory does not depend only on the length of step, and thus does not depend on the walking speed, [14].

The strong correlation between the 2-D plot of CoP displacement and 3-D plot of the CoP displacement vs. GRF was expected since the calculation of the 3-D plot takes the CoP displacement into account. However, a strong correlation was found only in the case of Pts. This is probably associated with higher GRFs in the case of HS, and thus the suppression of the effect of CoP position on the results.

According to the described findings, new parameters (trajectory length of 2-D plot of normalized CoP displacement and trajectory length of 3-D plot of normalized CoP displacement vs. normalized vertical GRF over one step) are less dependent on walking speed and thesignificant differences between the gait of Pts and HS, may yield an insight into balance and gait problems. However, it is necessary to consider that the accuracy of the calculation of the parameter (especially trajectory length) depends significantly on the sampling rate of the force platforms. The higher sampling frequency, the more accurate result of calculation. This reason makes it instrumental to use force platforms with higher recording frequencies. Nevertheless, the advantage of the proposed methods based on the trajectory length is their ability to study also, for example, deviations caused by tremor. Note that the

TABLE I. PARAMETER VALUES OF THE HEALTHY SUBJECTS (HS) AND PATIENTS (PTS).

		HS	Pts
d_{NCoP} (-)	***Min***	1.09	0.44
	Max	1.82	1.10
	Mean	1.40	0.76
	SD	0.19	0.25
$d_{NF\text{-}CoP}$ (N·kg^{-1})	***Min***	24.53	15.73
	Max	44.75	32.04
	Mean	36.81	25.43
	SD	4.97	5.39

Min - minimum; Max - maximum; SD - standard deviation; d_{NCoP} - total length of trajectory; $d_{NF\text{-}CoP}$ - length of the trajectory of the 3-D plot

TABLE II. CORRELATION COEFFICIENTS BETWEEN PARAMETER VALUES OF THE PATIENTS.

	d_{NCoP}	$d_{NF\text{-}CoP}$	v
d_{NCoP}	-	0.75**	0.33
$d_{NF\text{-}CoP}$	0.75**	-	0.03
v	0.33	0.03	-

**- strong correlation; d_{NCoP} - total length of trajectory; $d_{NF\text{-}CoP}$ - length of the trajectory of the 3-D plot; v (m·s^{-1})-walking speed.

TABLE III. CORRELATION COEFFICIENTS BETWEEN PARAMETER VALUES OF THE HEALTHY SUBJECTS.

	d_{NCoP}	$d_{NF\text{-}CoP}$	v
d_{NCoP}	-	0.23	0.30
$d_{NF\text{-}CoP}$	0.23	-	0.08
v	0.30	0.08	-

d_{NCoP} - total length of trajectory; $d_{NF\text{-}CoP}$ - length of the trajectory of the 3-D plot; v (m·s^{-1})-walking speed.

commonly used indices (maximum force, gait phase duration, etc.) cannot be used to identify gait problems caused by tremor during walking, or similar movement disorders. The methods can also be used to study the CoP and GRF measured during other types of movements, for example the transition from sitting to standing, [6].

There are a few limitations to our study. The major one is a relatively small sample of the subjects probably not representative of the larger population. However, for the sake of testing the basic attributes of the methods proposed for the study of gait using three force platforms in this preliminary study, a sample of seven Pts and ten HS is sufficient, just as in similar works [15]. Another limitation of this study is that only two measurements of each subject were performed. However, measurement of a subject with impaired postural stability is usually done only one or two times, or only data from a trial with the most complete and the longest record are used for further analysis [15]. This approach was chosen since some of the patients had significant stability problems and were unable to perform multiple tests. Limitation of this study may also be the different walking speed of Pts and HS. However, the objective of this study was to compare walking of HS and walking of Pts, and thus prove the applicability of described methods. In similar studies, [16]-[18], are also contemplated comfortable (freely) self-selected speed of walking, as compared characteristic and results of gait of HS and Pts. In following studies based on our preliminary study of proposed methods, we recommend the analysis of the effects of walking speed and set standards/norms for clinical practice.

V. CONCLUSION

The measurement of the CoP position and the size of the GRF and quantitative evaluation using new techniques provide an information on the gait as a whole. The new information on way of walking are the values of proposed indicators that show the differences in gait step as a whole. The described techniques and proposed parameters can be used for gait examination in clinical practice.

CONFLICT OF INTEREST

None to report.

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