Fourier Analysis of Center of Mass Trajectory in Hemiparetic Gait

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Abstract. Fourier analysis has been deeply explored and adopted in the investigation of human biomechanics and motion. Among objective biomechanical parameters, the human center of mass can be considered as an index of stability and symmetry. The current research focuses on the study of pelvis center of mass trajectory in hemiparetic gait by means of Fourier analysis. A symmetry index is applied on gait trials performed by control (5 males) and hemiparetic (12 males, 5 females) subjects. Among results, vertical symmetry indexes (0.94 healthy, 0.36 pathological) underline a significant difference between groups (p-value = 0.002). The promising methodology highlights the importance of biomechanically investigating the human locomotion in pathological patients.

Keywords: Gait · Fourier analysis · Hemiparesis · Symmetry · Center of mass

1 Introduction

Spectral analysis and Fourier series have been recently adopted for the analysis of human biomedical signals [1]. The principal attempt deals with the quantification of motion characteristics, such as smoothness and symmetry, starting from the harmonic biphasic or monophasic composition of signals [2, 3]. Considering the human locomotion and its cyclic behavior, several previous studies proposed several methodologies and instrumentations for the biomechanical investigation of gait impairments and long-term disabilities in clinical applications [4]. Among them, some researches adopted the Fourier mathematical approach for the analysis of kinematic signals of the human body, such as positions and accelerations [5–7], and the recognition of gait descriptors.

Among biomechanical variables, the 3D path of the body Center Of Mass (COM) during gait represents the translation of the body system as a whole and can be effectively considered as an indicator of body stability and symmetry [8]. The body COM position can be indirectly computed by force platforms and motion capture systems [9], through anthropometric measures and mass distribution. During healthy gait, the COM describes a 3D cyclic pattern, as reported in Fig. 1A. Considering a single gait stride (Fig. 1B), the vertical COM trajectory has two minimal and two maximal points, reflecting the symmetrical characteristics between the two lower limbs. Moreover, in

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case of symmetry, the 3D COM pattern presents just even harmonics in the progression and vertical directions, odd harmonics in the lateral one. In pathological gait, despite the maintenance of periodicity, the COM might depict a modified shape.

Different literature studies have investigated methods for the estimation of COM and the definition of mathematical symmetry indexes during gait [10]. Among them, Do Carmo et al. proposed the investigation of the body COM translation in stroke gait disturbances with the correlation between 3D displacements and singular gait phases [11]. In clinical gait analysis, usually only the reconstruction of the lower body is considered (i.e. two lower limbs and pelvis) due to the complexity and time consuming characteristics of the full body model. Therefore, the COM of the pelvis is calculated and largely used as the approximation of the full body COM [12]. Recently, Ochoa-Diaz et al. have investigated the pelvis COM trajectory in amputee gait using the Fourier series [13].

The current study deals with the application of Fourier analysis on pelvis COM trajectory in hemiparetic gait. Hemiparesis is described by slow and stiff movements, with a reduction of range of joints motion [14]. A stereophotogrammetric system and lower-limb kinematic model are used for the estimation of pelvis COM trajectory during gait, both in healthy and pathological subjects. The experimental measures are postprocessed to extract symmetry indexes for both groups of subjects, and the results are analyzed to confirm the suitability of harmonic index in the characterization of the hemiparetic gait.

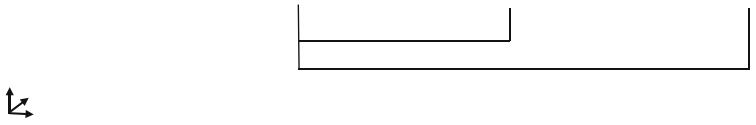

Fig. 1. A) 3D pelvis COM trajectory; B) COM trajectory in the sagittal plane and gait phases.

2 Material and Methods

Tests with healthy subjects were conducted in the POLITO BIOMed LAB of Politecnico di Torino, Italy. Patients performed tests in the Movement Disorders Center of Unità Spinale Unipolare – Città della Salute e della Scienza di Torino, Italy.

2.1 Participants

22 participants from different categories were recruited for the present study. Subjects classification (healthy and pathological), description and anthropometric data are reported in Table 1. All patients respected the following inclusion criteria: diagnosis of hemiparesis of lower limb, absence of orthopedic comorbidity and dementia, no prosthesis. Among them, 7 subjects walked with an external assistance, 10 subjects without

any assistance. The study was approved by the local Institutional Review Board for the healthy subjects. Procedures were confirmed to the Helsinki Declaration. For the pathological subjects, the study was approved by the Hospital Ethics Committees.

Table 1. Mean ±SD anthropometric data of healthy and pathological subjects

	Description	Age (years)	Weight (kg)	Height (m)
Healthy	5 healthy young male, no musculoskeletal/neurological diseases	28 ± 1	75 ± 8	1.83 ± 0.04
Pathological	9 hemiparetic patients (6 male, 3 female) with age < 65 years	47 ± 12	69 ± 12	1.71 ± 0.07
	8 hemiparetic patients (6 male, 2 female) with age > 65 years	73 ± 4	71 ± 8	1.74 ± 0.08

2.2 Task and Instrumentation

Experimental tasks were performed in laboratory environment and stereophotogrammetric systems were used for the data acquisition and elaboration. Two instruments setting were adopted based on the subjects' categories:

- 12 infrared-cameras Vicon Vero v2.2 (2048 × 2048 resolution, 100 Hz) and 3 video cameras Vicon VUE (1080p, 50 Hz) for the healthy subjects;
- 8 infrared-cameras Vicon Bonita 10 (1024 × 1024 resolution, 100 Hz) and 2 video cameras Vicon VUE (1080p, 50 Hz) for the pathological subjects.

Sixteen passive markers were positioned on anatomical landmarks for the reconstruction of the lower limb Plug-in-Gait (PiG) model [15, 16]. The subjects were initially required to assume a static posture for the model calibration. Starting from the 3D position of markers on the lower limbs, the pelvis COM is computationally obtained as the segmental kinematic centroid of human body from the weighted combination of mass and geometry of all modeled rigid segments [15, 16]. The subjects were asked to walk barefoot along an 8–10 m path at a self-selected velocity. Each participant performed four trials with the attempt to record 40–50 valid strides.

2.3 Data Analysis

The 3D pelvis COM trajectory and the identification of gait events were elaborated with the PiG dynamic pipeline in Vicon Nexus, while signals post-processing and data analysis were implemented with customized Matlab routines. The pelvis COM trajectory was calculated with respect to a reference system positioned in the center of the capture volume and with axes oriented as the anatomical local reference system of the pelvis. The pelvis reference system was described by y-axis (mediolateral direction) obtained

from the distance between markers on left and right anterior pelvis landmarks, z-axis (vertical direction) pointing upward orthogonally with respect to the floor and the x-axis (progression direction) calculated as the cross product between the two axes.

The pelvis COM signal, acquired for each gait trial, was then segmented into individual strides. For each stride, a representative index of symmetry was obtained by using the Discrete Fourier Series (DFS) [13]. The general formulation of the DFS considers a discrete periodic sequence $x[n]$. with a period of N samples such that $x[N+n] = x[N] \forall n$. The k^{th} DFS coefficient $c_k \in \mathbb{C}$ reads

$$c_k = \sum_{n=0}^{N-1} x[n] e^{-ik\omega_0 n}, \quad \omega_0 = \frac{2\pi}{N}, \quad k = 1, 2, \ldots, N-1, \tag{1}$$

where ω_0 is the fundamental frequency, i is the imaginary unit, k is the harmonic index.

When applying the DFS to gait analysis, symmetry indexes can be defined by inspecting the contributions of even and odd harmonics. Due to the nature of gait, the vertical trajectory is supposed to be described by an even function in healthy subject, since the contact of the two legs with the ground defines two symmetrical steps. Conversely, the mediolateral trajectory is described by a single sway during one stride, thus resulting in an odd function. Based on these observations, the vertical (S_{VL}) and mediolateral (S_{ML}) indexes are defined as [13]:

$$\begin{aligned} S_{VL} &= \frac{\sum_p^H |c_p|^2}{\sum_j^H |c_j|^2} \quad p = 2, 4, 6, \ldots H, \quad j = 1, 2, 3, \ldots H, \\ S_{ML} &= \frac{\sum_p^H |c_q|^2}{\sum_j^H |c_j|^2} \quad q = 1, 3, 5, \ldots H, \quad j = 1, 2, 3, \ldots H. \end{aligned} \tag{2}$$

Symmetry indexes range is between 0 and 1. When considering a healthy physiological gait, the indexes are close to 1. Given that the definitions of Eq. (2) are based on a ratio of DFS coefficients, the gait velocity does not affect the resulting indexes.

In the present study, the mean value was removed for each gait cycle and Eqs. (1)–(2) were used to obtain the DFS coefficients associated to the segmented COM trajectories, both in the vertical and mediolateral directions. Symmetry index was not calculated for the progression axis trajectory due to its monotonic trend. The analysis was limited to the first 10 harmonics (H = 10). This limit was set based on the sampling frequency (100 Hz) and on a priori inspection of the frequency spectra of the signals.

The limp index (0< value <1), defined as the ratio between right and left stance phases, was obtained and considered as a gold standard for the assessment of symmetry.

The normality of data distribution has been rejected with the Shapiro-Wilk test ($\alpha = 0.05$). A non-parametric Mann-Whitney test (significance $\alpha = 0.05$) was implemented to test the differences between groups. Pathological subjects were divided in two sub-groups based on: (i) age (lower or higher than 65 years old) and (ii) presence of external assistance during walking (without and with assistance). A non-parametric Kruskal-Wallis test (significance $\alpha = 0.05$) and Dunn's post hoc test were used to test the differences among the results obtained for the different groups and sub-groups.

3 Results and Discussion

Results are reported comparing healthy and pathological subjects. As a deeper investigation, patients have been grouped in different classes.

Figure 2 depicts an example of the COM trajectory during a stride for a healthy (green) and a pathological (red) subject. COM trajectories are projected in the three directions of motion: progression (A), mediolateral (B) and vertical (C). The progression curve (Fig. 2A) shows a monotonic pattern, but with a reduced slope in the pathological subject resulting from a reduced stride length. The mediolateral curve (Fig. 2B) describes a single periodicity in both subjects, although with different trends. The vertical signal (Fig. 2C) of the healthy subject clearly shows a periodic and repeatable pattern [13], with the two periods corresponding to each foot step. A remarkable loss of periodicity between the two steps in the gait cycle can be deduced instead from the pathological curve. This is associated with a flat trajectory during the stance phase of the hemiparetic limb. These results are in line with previous study on post-stroke patients [11].

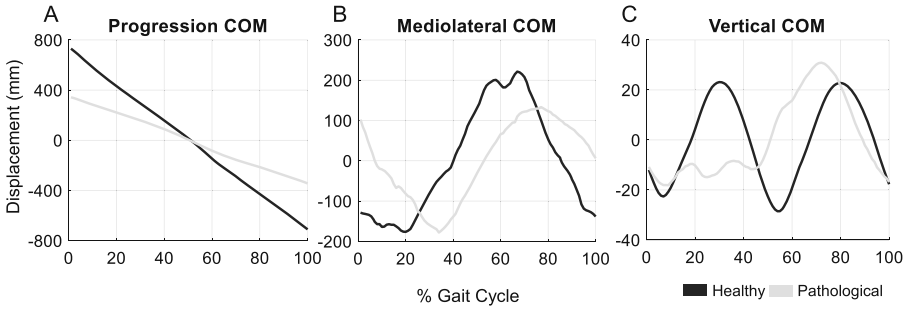

Fig. 2. Pelvis center of mass trajectory in one healthy (green) and one pathological (red) subject.

Figure 3 shows the Fourier coefficients of mediolateral signals for the same healthy (A) and pathological (B) subjects. As expected, the mediolateral COM trajectory of the healthy subject is dominated by the first harmonic (Fig. 3A), and this is clearly reflected to its composition in the time domain (Fig. 3C). The same predominance resulted for the pathological subject (Fig. 3B–D), but with an increase of the second harmonic.

Figure 4 shows the Fourier coefficients of vertical signals for the healthy (A) and pathological (B) subjects. The vertical COM of the healthy subject is dominated by the second harmonic, as also depicted in its time composition (Fig. 4C). On the contrary, the distribution of the Fourier coefficients is more scattered for the pathological subject, with comparable values among even and odd harmonics. As showed in Fig. 4D, both first (red) and second (blue) harmonics highly contribute to the signal composition.

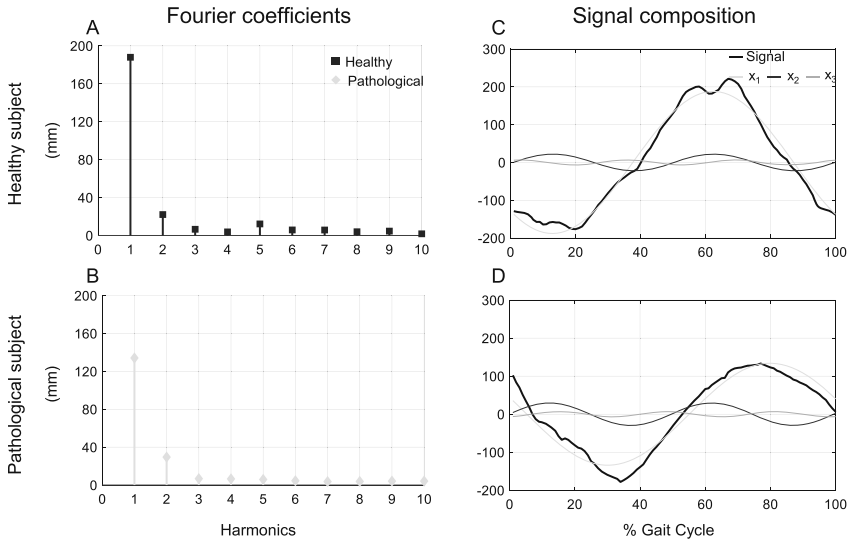

Fig. 3. Fourier coefficients of the mediolateral COM signals for one healthy (A) and one pathological (B) subject; signal composition of the first three harmonics in healthy (C) and pathological (D) subject.

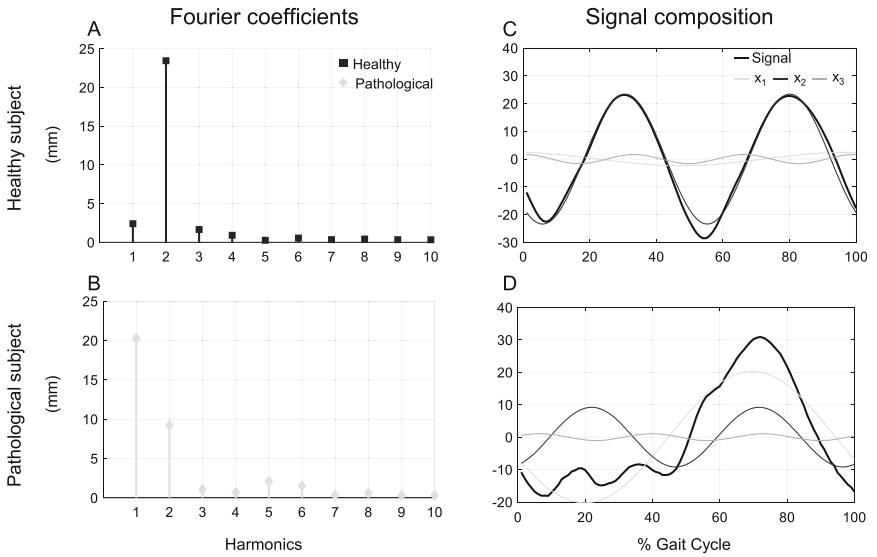

Fig. 4. Fourier coefficients of the vertical COM for one healthy (A) and one pathological (B) subject; signal composition of the first three harmonics in healthy (C) and pathological (D) subject.

Symmetry indexes have been calculated and averaged among the different strides of each subject (intra-subject) and then among the different subjects (inter-subject). The scatter plots represented in Fig. 5 A–B show the distribution of mediolateral and vertical symmetry indexes calculated for each stride of each patient. Each patient is depicted with a different color. These graphical results highlight the larger intra-subject variability in mediolateral indexes with respect to the vertical ones. Possible reasons might be addressed to the several compensatory schemes adopted by the patients, which can differ also among strides. For this reason, the vertical coordinate of pelvis COM translation seems more representative of gait asymmetry in hemiparesis.

Table 2 sums up the estimation of mediolateral (S_{ML}) and vertical (S_{VL}) symmetry indexes both in healthy and pathological subjects. Mean values show a strong reduction of symmetry in vertical COM, and a discrete reduction in mediolateral COM. The statistical comparison between the two groups highlights a significant difference for both the directions (p-value $= 0.02$ for S_{ML}, p-value $= 0.002$ for S_{VL}), but with stronger significance on the vertical one. In the patients' classification based on age and assistance, the asymmetrical characteristic of gait persists in all groups. No significant differences have been pointed out in the comparison among pathological groups (p-value > 0.05). Each group maintained the significant difference with respect to the control group.

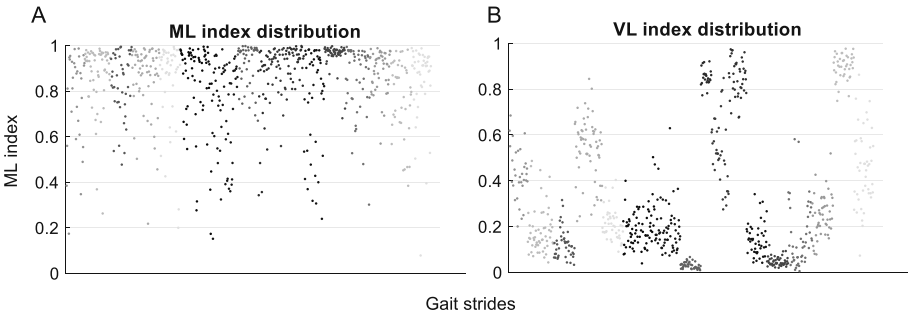

Fig. 5. Distribution of Mediolateral (A) and Vertical (B) indexes calculated for each stride of pathological subjects. Each patient is represented by a different color.

The limp index confirmed the symmetry in healthy subjects (value $= 1$) and the asymmetry in pathological subjects (value $= 0.84$), with significant difference between the two groups. Statistical analysis of the patients' classification revealed same results, validating the suitability of Fourier series and harmonic index to depict gait symmetry.

Table 2. Mean (SD) Symmetry indexes in all healthy and pathological conditions

Symmetry index	Healthy subject	Pathological subject	p-value
S_{ML}	0.93 (0.02)	0.84 (0.08)	**0.02**
S_{VL}	0.94 (0.02)	0.36 (0.29)	**0.002**
Limp index	1 (0.01)	0.84 (0.02)	**0.003**

Pathological classification

Symmetry index	Age < 65	Age > 65	Without ass.	With ass.
S_{VL}	0.47 (0.34)	0.23 (0.13)	0.44 (0.34)	0.24 (0.14)
p-value	0.31		0.47	
p-value (VS control)	**0.026**	**0.002**	**0.014**	**0.003**
Limp index	0.85 (0.03)	0.83 (0.02)	0.86 (0.03)	0.81 (0.02)
p-value	0.39		0.36	
p-value (VS control)	**0.022**	**0.002**	**0.017**	**0.002**

4 Conclusion

The current study focused on the investigation of symmetry in hemiparetic gait through the Fourier analysis of pelvis COM trajectory. Experimental tests demonstrated the importance of the biomechanical investigation of the pelvis COM vertical trajectory with Fourier analysis and the possibility to represent human gait symmetry with a global harmonic descriptor. Significant differences between healthy and pathological subjects have been pointed out in signals harmonic contents and in symmetry index values. Some limitations of the study could be identified in the variability among subjects and the limited number of strides. Future tests with different indexes, a larger population, and different clinical circumstances (i.e. before and after treatment) will be conducted. Additional analysis on different pathological conditions might confirm the suitability and feasibility of investigating only the vertical trajectory or the necessity to include a 3D investigation of the COM for a clinical characterization.

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References

1. Krishnan, S., Athavale, Y.: Biomedical signal processing and control trends in biomedical signal feature extraction. Biomed. Sig. Process. Control **43**, 41–63 (2018). https://doi.org/10.1016/j.bspc.2018.02.008

2. Bellanca, J.L., Lowry, K.A., VanSwearingen, J.M., Brach, J.S., Redfern, M.S.: Harmonic ratios: a quantification of step to step symmetry. J. Biomech. **46**, 828–831 (2013)
3. Panero, E., Digo, E., Dimanico, U., Artusi, C.A., Zibetti, M., Gastaldi, L.: Effect of deep brain stimulation frequency on gait symmetry, smoothness and variability using IMU. In: 2021 IEEE International Symposium on Medical Measurements and Applications, MeMeA 2021 - Conference Proceedings (2021). https://doi.org/10.1109/MEMEA52024.2021.9478602
4. Panero, E., Dimanico, U., Artusi, C.A., Gastaldi, L.: Standardized biomechanical investigation of posture and gait in Pisa syndrome disease. Symmetry (Basel) **13** (2021). https://doi.org/10.3390/sym13122237
5. Minetti, A.E., Cisotti, C., Mian, O.S.: The mathematical description of the body centre of mass 3D path in human and animal locomotion. J. Biomech. **44**, 1471–1477 (2011)
6. Iosa, M., et al.: Stability and harmony of gait in patients with subacute stroke. J. Med. Biol. Eng. **36**, 635–643 (2016). https://doi.org/10.1007/S40846-016-0178-0
7. Lowry, K.A., Smiley-Oyen, A.L., Carrel, A.J., Kerr, J.P.: Walking stability using harmonic ratios in Parkinson's disease. Mov. Disord. **24**, 261–267 (2009). https://doi.org/10.1002/mds.22352
8. Tesio, L., Rota, V.: The motion of body center of mass during walking: a review oriented to clinical applications. Front. Neurol. **10**, 999 (2019). https://doi.org/10.3389/FNEUR.2019.00999
9. Shanahan, C.J., et al.: Technologies for advanced gait and balance assessments in people with multiple sclerosis. Front. Neurol. **8** (2018)
10. Viteckova, S., Kutilek, P., Svoboda, Z., Krupicka, R., Kauler, J., Szabo, Z.: Gait symmetry measures: a review of current and prospective methods. Biomed. Sig. Process. Control. **42**, 89–100 (2018). https://doi.org/10.1016/j.bspc.2018.01.013
11. Do Carmo, A.A., Kleiner, A.F.R., Barros, R.M.L.: Alteration in the center of mass trajectory of patients after stroke **22**, 349–356 (2015). https://doi.org/10.1179/1074935714Z.0000000037
12. Saini, M., Kerrigan, D.C., Thirunarayan, M.A., Duff-Raffaele, M.: The vertical displacement of the center of mass during walking: a comparison of four measurement methods. J. Biomech. Eng. **120**, 133–139 (1998). https://doi.org/10.1115/1.2834293
13. Ochoa-Diaz, C., Bó, A.P.L.: Symmetry analysis of amputee gait based on body center of mass trajectory and discrete Fourier transform. Sensors **20**, 2392 (2020)
14. Celik, Y., Stuart, S., Woo, W.L., Godfrey, A.: Gait analysis in neurological populations: progression in the use of wearables (2021)
15. https://docs.vicon.com/display/Nexus212/Kinetic+modeling. Accessed 07 Apr 2022
16. Davis, R.B., Õunpuu, S., Tyburski, D., Gage, J.R.: A gait analysis data collection and reduction technique. Hum. Mov. Sci. **10**, 575–587 (1991). https://doi.org/10.1016/0167-9457(91)90046-Z