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Spectral parameters of gait differentiate diabetic patients from healthy individuals

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ABSTRACT

Background: Diabetes mellitus (DM) is a clinical condition that affects gait performance and control in millions of individuals worldwide. Contrary to basic spatiotemporal parameters, gait-based spectral analysis may provide useful insights into gait neuromotor control. Hence, this study was set to investigate the spectral content of gait at the preferred speed in patients with DM.

Methods: Total 1117 individuals [658 DM and 649 healthy adults (HA)] performed a 10 m walk while wearing an inertial measurement unit over the fourth lumbar vertebra. Mann-Whitney-U test was used for between-group gait parameters comparisons.

Results: DM group had a slower step time (1.2%, $p < 0.05$) and gait speed (2.4%, $p < 0.05$) than HA. Additionally, DM individuals showed reduced dominant frequency (DM:0.24 *Hz vs* HA:0.25 *Hz* on average, $p < 0.05$). Increased antero-posterior and vertical dominant frequency width (DM:1.73 *Hz vs* HA:1.76 *Hz* on average, $p < 0.05$) and medio-lateral relative power spectral density at the dominant frequency (DM:6.19% *vs* HA:5.96%, $p < 0.05$).

Conclusions: It was demonstrated for the first time that the gait spectral content, not only corroborates spatiotemporal characteristics, but also provides further insight into their neuromotor control deficits in diabetic patients. Ultimately, this type of analysis in the diabetic population can help guide the therapeutic interventions to prevent diabetic foot.

1. Introduction

In 2014, an estimated 422 million adults were living with diabetes mellitus (DM) worldwide, where approximately 90% suffered from type II DM [1,2]. This number has increased fourfold since 1980 and currently carries a global financial burden greater than US$ 827 billion [2,3]. As DM affects a multitude of systems, it often leads to several comorbidities, such as diabetic retinopathy, renal disease, cardiovascular complications and peripheral neuropathy [4–7], ultimately contributing to reduced life expectancy [2]. The nervous system of DM patients also experiences developing limitations, such as deficits in motor-neuron excitability and conduction velocity [8,9] and enlargement of peripheral nerves, involved in sensorimotor polyneuropathy and in potential neuromuscular performance declines [10].

Although acute hyperglycaemia doesn't seem to affect the capacity of the skeletal muscle to generate tension, accumulating evidence supports that chronic hyperglycaemia, such as experienced in DM patients, can lead to neuromuscular performance impairments [10–14].

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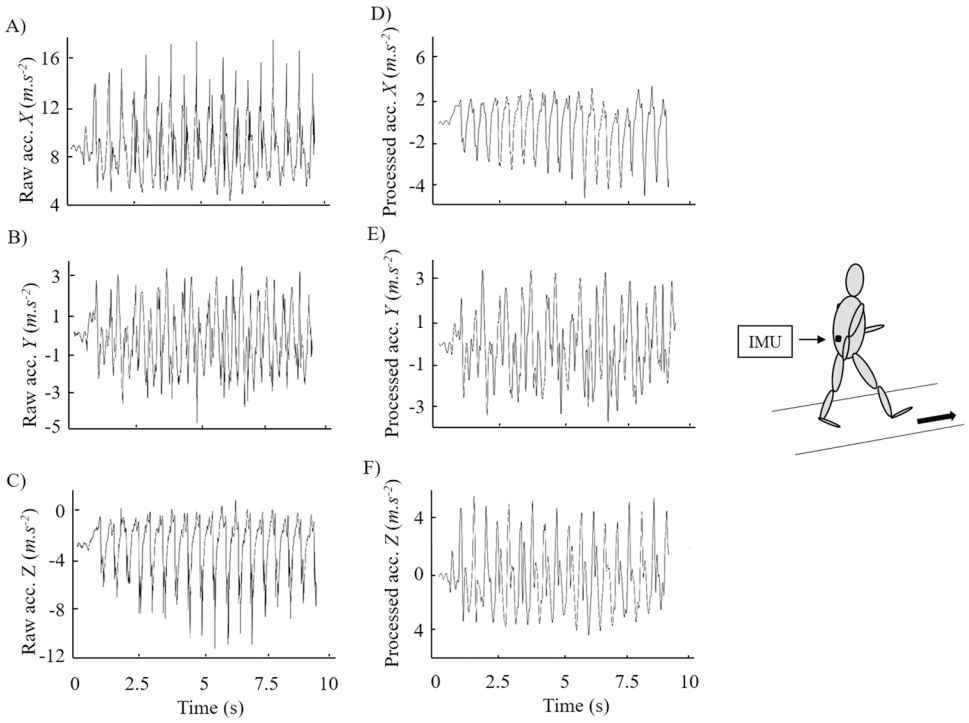

Fig. 1. Exemplar of raw acceleration in the *X* (A), *Y* (B) and *Z* axis (C) and processed acceleration (rotated, gravidity corrected and filtered) in *X* (D), *Y* (E) and *Z* axis (F), during a representative 10 m walking trial.

Specifically, there are reports of delayed reaction time, deficits in the generation of muscle strength and power and reduced oxidative capacity among DM patients [15–17]. Considering these neuromuscular deficits, it is not surprising that individuals with DM have impaired ability to ambulate in a stable and effective fashion [18,19].

Normal walking depends on a series of biomechanical events that optimizes energy expenditure and stability, regulated by the complex organization of the afferent and efferent information in the central nervous system [20,21]. DM patients tend to show slower gait speeds, shorter stride length, greater stride length variability and step width and altered proportions of stance and swing times [17,22].

While spatiotemporal characteristics of gait are frequently used to characterize and identify deficits in gait in a multitude of populations, they have a limited capability to infer about neuro-motor control [17, 23–30]. In contrast, the spectral content (frequency domain) of physiological signals can provide further interpretation from what can be retrieved from spatiotemporal analysis [31]. For example, it has been suggested that the frequency domain of surface electromyography can allow for probing the integrity of corticospinal tracts and provide a deeper understanding of neural mechanisms of motor control [31,32]. Furthermore, frequency domain analysis of pelvic acceleration has been used to reflect mechanisms of neuro-motor control of gait [33,34].

Although spectral analysis has been often used to investigate a multitude of biological signals, it has only been used in a few instances to investigate gait in different populations and consequently adding valuable information about instability, asymmetry, variability and freezing of gait [35–41]. Nonetheless, to the best of our knowledge, this approach has never been applied to the DM population. It is possible that spectral content of DM patient's gait patterns can allow for a more comprehensive understanding of the frequently reported spatiotemporal deficits.

To address for the existing gap in knowledge, this study proposed to investigate the spectral content of gait at the preferred speed in patients with DM. The authors hypothesized that the spectral content analysis will result in (at least) a similarly effective differentiation as the spatiotemporal parameter, between DM patients and healthy adults (HA).

2. Materials and methods

2.1. Participants

Participants were included whose condition was stable (in terms no relapse or exacerbation, causing a significant change in their condition), who could walk at least 10 m independently with or without their walking aid(s). Participants will be excluded who were pregnant or allergic to adhesive materials, had a condition that precludes safe participation in assessment as indicated by referring clinician, had insufficient mental capacity to consent (according to the mental capacity act), demonstrated uncontrolled psychiatric symptoms, had a mobility index (Rivermead Mobility Index (RMI);[42]) less than 8. In addition participants had no confounding factors in addition to Diabetes Mellitus Type 2, such as other neurological conditions, knee replacements, amputations or shoes with padding. All participants provided written consent approved by the Research Ethics Committee of Shanghai Sixth People's Hospital Affiliated to Shanghai Jiao-Tong University (2016–42).

2.2. Protocol

Participants walked straight for the length of 10 m at their preferred speed while wearing an inertial measurement unit (IMU, LPMS-B, Life Performance Research, Japan) that was fixed with adhesive tape over the participant's fourth lumbar vertebra (L4) to emulate the motion of the participant's centre of mass (CoM). The IMU was used to record triaxial accelerometry during the walking task and collected data at a sampling frequency of 100 Hz [43].

2.3. Data analyses

LabVIEW (National Instruments, Newbury, UK) was used to extract and calculate the spatiotemporal outcome variables.

IMU vectors were rotated into the global frame, and double integrated resulting in true-vertical CoM excursion [43]. Step time was

Table 1
Participant demographics.

	DM	HA
	(*n*=*568*, 30.8% male)	(*n*=549, 30.8% male)
Age (*years*)	52.9 (0.4)	52.8 (0.6)
Height (*m*)	1.63 (0.01)	1.62 (0.01)
Weight (*kg*)	66.3 (0.5)[a]	63.7 (0.6)
BMI	24.8 (0.2)[a]	24.0 (0.2)
Haptoglobin Genotype (%)	34.3	18.9
Peripheral Neuropathy (%)	2.3	0.7
Smoking (%)	20.5	8.5
DM Diagnosis (*years*)	7.5 (0.3)	
Diabetic foot (%)	1.6	

Data shown as Mean (SEM). HA – healthy adults; DM – diabetes mellitus.
[a] represents a significant difference from HA.

Table 2
Spatiotemporal characteristics of gait.

	DM	HA
	(*n*=*568*, 30.8% male)	(*n*=549, 30.8% male)
Step Time (*s*)	0.52 (0.01)[a]	0.51 (0.01)
Cadence (*steps/min*)	117.0 (0.5)	118.4 (0.6)
Gait Speed ($m.s^{-2}$)	1.26 (0.01)[a]	1.29 (0.01)
Normalized Stride Length	1.44 (0.01)	1.42 (0.01)

Data shown as Mean (SEM). HA – healthy adults; DM – diabetes mellitus.
[a] represents a significant difference from HA.

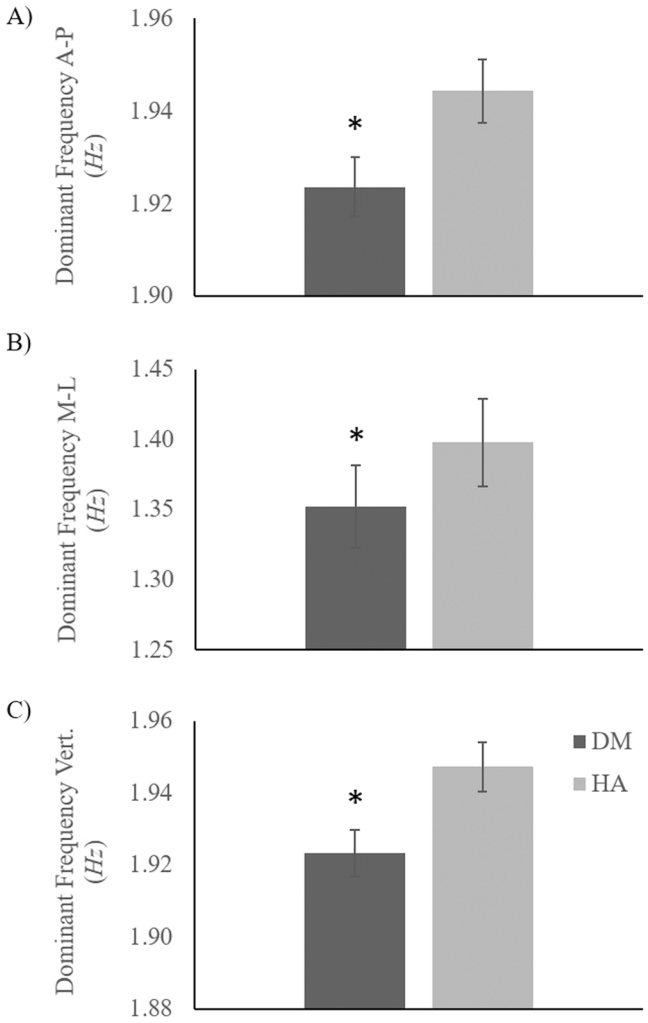

Fig. 2. Antero-posterior (A-P) (A), medio-lateral (M-L) (B) and vertical (Vert.) (C) dominant frequencies during walking at the preferred speed, in diabetic mellitus patients (DM) and healthy adults (HA). * represents a significant difference from HA ($p < 0.05$).

calculated as CoM vertical peak differences [ms], Gait Cadence was derived from the centre frequency of the vertical CoM movement over the whole 10-metre walks [steps/min], gait speed.

Gait speed was calculates on a step-by-step basis, as stride length (derived using inverted pendulum methodology, driven by vertical CoM excursion) per step-time and averaged over the whole walk [m*s-1]. Stride length was normalised (normalized stride length) to leg length [m], to offset any height differences [44] within the population. Medio-lateral displacement consisted of the difference between the right and left IMU maximum relative positions between steps.

A custom MATLAB (MathWorks, Natick, MA) program was used to calculate the three-dimensional linear acceleration in the participant's reference frame from the IMU dataset.

Similar to previous reports, the raw acceleration was rotated to the participant's reference frame, so that the *x*, *y* and *z* axes represent antero-posterior, medio-lateral and vertical motion, respectively. Subsequently, a gravity correction was applied to the rotated acceleration and filtered using a 4th order Butterworth band-pass filter (0.2–15 Hz) [40,45].

Spectral analysis was performed by applying a 256 point Fast Fourier Transform (FFT) to the filtered acceleration allowing for the calculation of the power spectral density (PSD) through Welch's method and periodic Hanning window, with a 50% overlap [46]. This procedure was applied to the frequency band of 0.5–3 Hz, which encompasses the locomotor frequency band [41].

The dominant frequency was identified as the frequency where the dominant PSD peak occurs.

Dominant frequency width was calculated by the Full Width at Half-Maximum method, as the width of the PSD curve that contained the dominant PSD peak.

Relative PSD was defined as the proportion of PSD at the dominant frequency and expressed as a percentage of the total PSD of the full spectrum.

The filtered acceleration was also used to calculate relative position through a double integration procedure previously described in detail (Fig. 1) [43].

2.4. Statistical analyses

An initial Shapiro-Wilk test was performed to assess normality of distribution of the outcome variables. As the vast majority of the outcome variables showed a non-normal distribution, between-group comparisons were performed using the non-parametric test Mann-Whitney U (SPSS v22, IBM, Armonk, NY). Significance was set at $p<0.05$.

3. Results

A total of 1117 individuals were recruited from Shanghai Sixth People's Hospital affiliated to Shanghai Jiao Tong University, where 568 (31% male) had diagnosed DM and 549 (31% male) were age and gender-matched otherwise healthy adults (HA) (Table 1).

Step time and gait speed were slower among diabetic patients (DM) compared to healthy (HA) individuals (1.2% and 2.4% respectively, $p < 0.05$, Table 2). Cadence and normalized stride length were not significantly different between groups ($p > 0.05$, Table 2).

Antero-posterior (DM: 1.92 ± 0.01 *Hz vs* HA: 1.94 ± 0.01 *Hz*, Fig. 2A), medio-lateral (DM: 1.35 ± 0.03 *Hz vs* HA: 1.40 ± 0.03 *Hz*, Fig. 2B) and vertical dominant frequency was reduced ($p < 0.05$) (DM: 1.92 ± 0.01 *Hz vs* HA: 1.95 ± 0.01 *Hz*, Fig. 2C) for diabetic patients (DM) compared to healthy individuals (HA).

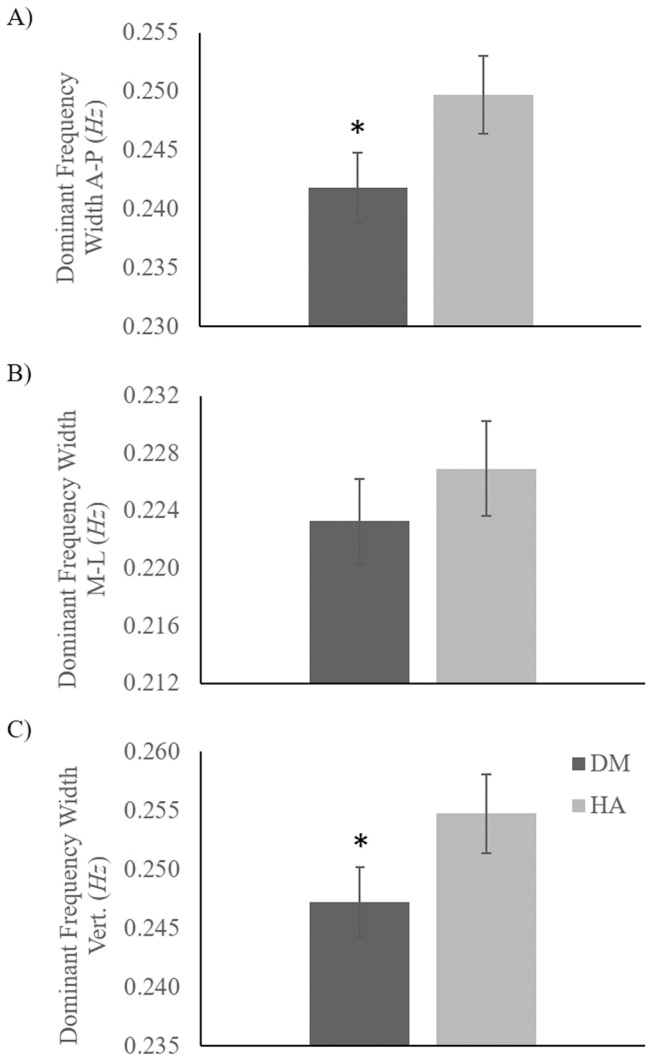

Fig. 3. Antero-posterior (A-P) (A), medio-lateral (M-L) (B) and vertical (Vert.) (C) dominant frequency width during walking at the preferred speed, in diabetic mellitus patients (DM) and healthy adults (HA). * represents a significant difference from HA ($p < 0.05$).

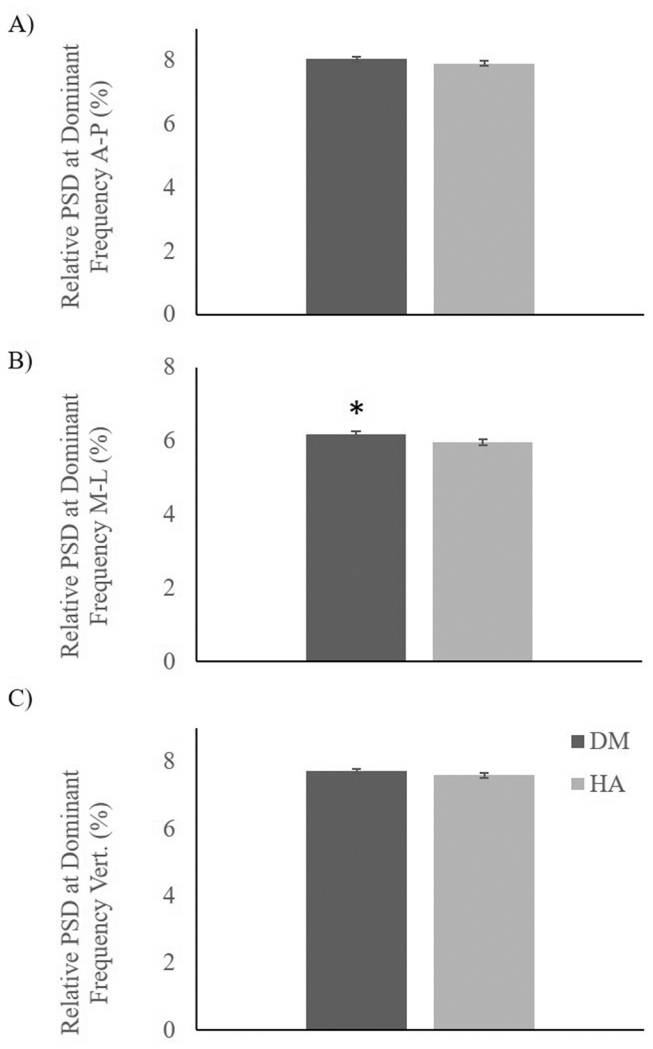

Fig. 4. Antero-posterior (A-P) (A), medio-lateral (M-L) (B) and vertical (Vert.) (C) relative PSD at the dominant frequency during walking at the preferred speed, in diabetic mellitus patients (DM) and healthy adults (HA). * represents a significant difference from HA ($p < 0.05$).

Dominant frequency width was smaller for DM individuals for antero-posterior (DM: 0.24 ± 0.01 *Hz vs* HA: 0.25 ± 0.01 *Hz*, $p < 0.05$, Fig. 3A) and vertical directions (DM: 0.25 ± 0.01 *Hz vs* HA: 0.26 ± 0.01 *Hz*, $p < 0.05$, Fig. 3C). Medio-lateral dominant frequency width was similar between groups ($p > 0.05$).

DM patients also showed a greater relative power spectral density (PSD), but only at the dominant frequency medio-lateral (DM: 6.19 ± 0.08% *vs* HA: 5.96 ± 0.08%, $p < 0.05$, Fig. 4B). Relative PSD was similar between both groups for antero-posterior and vertical dominant frequency ($p > 0.05$).

4. Discussion

The observations from the present study show that gait spectral analysis has a superior discriminative power compared to basic spatiotemporal parameters during a 10 m walk, therefore supporting the hypothesis. In addition, the results show that the spectral content of gait provides an increased differential power to spatiotemporal outcomes as per hypothesis, and can provide new insights into underlying mechanisms of diabetes affecting mobility.

Considering the existing body of literature, it was expected to observe significant differences between both groups in the evaluated spatiotemporal characteristics [17,22]. In this study, the diabetic patients showed a similar cadence and stride length to their healthy counterparts, but as anticipated, they showed slower stepping and gait speeds. However, there is a high level of heterogeneity of gait velocity reduction in DM, as some authors have reported increased gait velocity in those with DM, with or without peripheral neuropathy [47,48]. In fact, previous meta-analysis has revealed no difference in gait velocity or stride length when comparing those with and without DM [49].

Previous reports suggest that the diabetes-dependent alterations in the nervous system may affect the neuromotor control precipitating these spatiotemporal deficits, even in the absence of peripheral neuropathy [22]. The spectral analysis provided further insights in the neuromotor control of diabetic gait. Considering the significantly slower walking speeds in the diabetic group, it was not surprising to observe a significantly lower dominant frequency in these individuals. Due to being driven by the walking speed, these results are also supported by previous reports from other clinical populations, also showing reduced gait speeds compared with healthy individuals [34,40].

The dominant frequency width was lower in diabetic patients for all axis. The width of the curve of the dominant frequency reflects the frequency dispersion and has been used as a marker of variability of gait [40,41]. Although, impaired gait is often accompanied by increased variability [34,35], reduced gait variability has also been identified

among some clinical populations [41]. The present results demonstrate that this cohort of diabetic patients had lower variability of gait. This reduced variability may represent an impaired capacity to adapt to external conditions and reflect more rigid neuromotor coordination gait patterns [41,50]. The findings from the relative PSD at the dominant frequency do not corroborate reports in other populations [34,40,41]. It would expect that the greater gait variability in DM patients would be also expressed in greater spectral energy dispersion around the dominant frequency. It is plausible that the frequency band selected for this particular variable was too narrow to discriminate DM and healthy individuals. Nonetheless, the significant results were only identified in the frontal plane. This may be explained, at least in part, by the trend for a reduced dominant frequency width in the frontal plane. It is conceivable that this lower variability in the medio-lateral neuromotor control, led to a greater concentration of spectral energy at the dominant frequency. In addition, it has also been highlighted that neuromotor control of the different planes may be different, possibly representing different control strategies [51].

Lastly, this study has a few limitations that need mentioning. Although the sample size is rather large, the non-random selection of the age and sex-matched controls might have influenced some of the results. Another potential limitation pertains to the effect the testing session had on the participant's motivation to perform. Considering its difference from a real life setting [41], it is possible that the controlled setting might have influenced the participants' "effort to perform better", particularly in the diabetic clinical group.

To the best of our knowledge, this study is the first to demonstrate that, for diabetic individuals, the spectral content of gait corroborated spatiotemporal findings and was also able to provide further insight in the neuromotor limitations experienced by this clinical population.

Hence, these spectral variables can provide useful insight on the control of gait that may not be captured by the traditional spatiotemporal analysis.

Ultimately, the application of spectral analysis to diabetic patient's gait can be potentially useful for early detection of individuals with diabetic neuropathy or vascular disorders in lower extremities and help guide the therapeutic interventions to achieve more adequate and effective outcomes in diabetes population.

Declaration of Competing Interest

None.

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